92-04790/

GEOLOGICAL SURVEY OF CANADA
MEMOIR 432

GLACIAL AND ENVIRONMENTAL GEOLOGY OF NORTHEASTERN MANITOBA

L.A. Dredge and F.M. Nixon

1992

© Minister of Supply and Services Canada 1992

Available in Canada through authorized
bookstore agents and other bookstores

or by mail from

Canada Communication Group — Publishing
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa, Canada K1A 0E8

3303-33rd Street N.W.,
Calgary, Alberta T2L 2A7

A deposit copy of this publication is also available for
reference in public libraries across Canada

Cat. No. M46-432E
ISBN 0-660-14399-2

Price subject to change without notice

Cover photo

Boreal scrub forest and subarctic peatlands with thermokarst ponds, along the Hudson Bay Railway. NAPL photo T169R-27.

Original manuscript received: 1989 - 04
Final version approved for publication: 1990 - 06

Preface

"The character and history of the growth of the land around Hudson Bay deserve much more study than they have yet received, and I feel quite convinced that the volume of new and valuable information which would be obtained from such a study would well repay the time and money spent on it."

J. B. Tyrrell
from: Presidential address to the Royal Society of Canada, May 1916.

This work, which describes and interprets terrain conditions across the Hudson Bay lowlands and adjacent Canadian Shield, was initiated 75 years after the need for extensive work on the glacial geology of the region was first recognized. The impetus for recent work was a need for mapping and characterizing earth materials and permafrost conditions for pipeline and hydro corridor planning in this tract of frozen muskeg. The glacial geology is particularly interesting because two major ice masses, belonging to different sectors of the Laurentide Ice Sheet, converged and interacted in the Churchill area: the glacial record is thus a key to understanding the structure and dynamics of the last ice age.

The report and accompanying map describe and interpret the terrain conditions across 48 000 km^2 of the coast and hinterland of Hudson Bay. The surface mapping of materials was combined with a study of river exposures in order to reconstruct the preglacial and glacial evolution of the landscape, and postglacial changes in permafrost, climate, and sea level. The geological interpretation was used to locate anomalously high concentrations of minerals of economic value, including gold and uranium, assess aggregate sources, identify areas of sensitive permafrost terrain, and to predict future environmental change.

Elkanah A. Babcock
Assistant Deputy Minister
Geological Survey of Canada

Préface

«La nature et l'histoire de la croissance du territoire autour de la baie d'Hudson méritent d'être étudiées beaucoup plus en détail qu'elles ne l'ont été jusqu'à maintenant. Je suis tout à fait convaincu qu'une telle étude fournirait un volume de renseignements nouveaux et utiles qui plus que compenserait le temps et l'argent requis pour exécuter les travaux.»

J.B. Tyrrell
(Citation tirée du discours du président prononcé devant la Société royale du Canada, en mai 1916.)

La présente étude, qui décrit et interprète les facteurs topographiques dans les basses terres de la baie d'Hudson et la partie contiguë du Bouclier canadien, a commencé 75 ans après que fut reconnu pour la première fois le besoin d'exécuter des travaux systématiques sur la géologie glaciaire de la région. Les travaux récents ont été menés en vue de cartographier et de décrire les matériaux terrestres et le pergélisol aux fins de la planification des tracés de pipelines et de lignes de transport d'énergie sur cette étendue de muskeg gelé. La géologie glaciaire suscite un intérêt particulier, car deux grandes masses de glace, qui appartenaient à des secteurs différents de l'inlandsis laurentidien, ont convergé et interagi à proximité de Churchill; les données glaciaires sont donc essentielles pour bien comprendre la structure et la dynamique de la dernière époque glaciaire.

Le rapport et la carte d'accompagnement présentent une description et une interprétation des facteurs topographiques sur une étendue de 48 000 km de la côte et de l'arrière-pays de la baie d'Hudson. En alliant la cartographie des matériaux en surface et l'étude des coupes le long des cours d'eau, il a été possible de reconstituer l'évolution préglaciaire et glaciaire du paysage, ainsi que les changements postglaciaires qu'ont subis le pergélisol, le climat et le niveau marin. Grâce à l'interprétation géologique, on a réussi à trouver des concentrations anormalement élevées de minéraux économiques, notamment l'or et l'uranium, d'évaluer les sources d'agrégats, de reconnaître les zones pergélisolées sensibles et de prévoir les changements environnementaux futurs.

Elkanah A. Babcock
sous-ministre adjoint
Commission géologique du Canada

CONTENTS

1 Abstract/Résumé

2 Summary/Sommaire

5 Introduction
5 Objectives
5 Field work
5 Scope of the report
6 Previous work
6 Bedrock
6 Glacial deposits
6 Bedrock geology
8 Physiography
11 Drainage
11 Climate

11 Surficial materials
11 Bedrock outcrop
11 Glaciated Precambrian outcrop
12 Paleozoic outcrop
12 Broken rock, felsenmeer
13 Till
13 Till of Keewatin provenance
16 Till of Hudson provenance
18 Glaciofluvial deposits
18 Conjugate ridges, crevasse fillings
19 Kame moraine
19 Kames
19 Eskers
19 Outwash
21 Glaciolacustrine deposits and landforms
21 Description and distribution
21 General nature of deposits
21 Sedimentary facies
23 Landforms
24 Glaciomarine and marine deposits
24 Distribution
24 Offlap sequence: undifferentiated marine deposits
24 Stony marine and glaciomarine deposits: stony pelite
25 Silty marine pelite
25 Intertidal silts
25 Blanket sands
25 Sand and gravel beach ridge complexes
25 Alluvium
25 Older alluvium
26 Modern alluvium
26 Peat
26 Forested bog peat with thermokarst ponds
26 Tundra peat with ice-wedge polygons
27 Wet fen peat
27 Coalesced peat blisters
27 Peat and mineral soil complexes: wet fen meadows with mudboils

28 Stratigraphic record
28 Sediment sequence

29 Saprolite
29 Harts Till: old Keewatin till
31 Amery Till
31 Nelson River sediments
33 Tills of the Wisconsin Glaciation
34 Lake Agassiz sediments
35 Knife Till (Cochrane equivalent)
35 Glaciomarine unit
35 Tyrrell Sea sediments
35 Alluvium and peat
35 Regional correlations

36 Glacial and postglacial history
36 Ice flow indicators
37 Pre-Wisconsin glaciations and the Sangamon Interglaciation
37 Wisconsin Glaciation
40 Deglaciation
40 Ice recession against Lake Agassiz
44 Readvance and catastrophic demise of Hudson ice
44 Recession of Keewatin ice to a final centre near Hudson Bay
44 Tyrrell Sea episode and postglacial sea level changes
44 Configuration and maximum extent
47 Age of marine transgression
47 Sea level changes
48 Sedimentation, beach ridge development, and coastal changes
50 Holocene evolution of lower Churchill River
50 Terrace levels and stages of downcutting
51 Postglacial climatic changes

52 Environmental geology and mineral exploration
52 Permafrost
52 Distribution of permafrost
53 Thermal conditions in the zone of continuous permafrost
55 Thermal conditions in discontinuous permafrost
55 Ground ice
55 Thermal sensitivity of peatlands
57 Engineering problems related to permafrost conditions
58 Recommendations
59 Buffering capacity of calcareous soils in cold regions against effects of acid rain
59 Land use concerns
59 Sand and gravel resources
60 Geotechnical properties of materials
60 Peat resources
61 Till geochemistry
61 Methods
61 Till types, bedrock, and ice flow
61 Base metal concentrations
61 Locations of anomalies

64 Acknowledgments

64 References

Appendix

67 Section descriptions 1 to 28

Tables

24 1. Characteristics used to differentiate between nonfossiliferous marine and lacustrine deposits
46 2. Radiocarbon dates
54 3. Physical properties of peat, and active layer depths
60 4. Engineering index properties of fine grained sediments

Illustrations

Map 1617A. Surficial geology, northeastern Manitoba *(in pocket)*

5 1. Location of study area
6 2. Bedrock geology and location of transects
7 3. Physiographic transects across northern Manitoba
9 4. Landscape units of northeastern Manitoba
10 5. Caribou plains region, north of Seal River
10 6. Hudson borderlands
10 7. Patterned peat plateau
10 8. The Great Beach
10 9. Forested bog with fens in thermokarst depressions
12 10. Roche moutonnée forms in Precambrian "quartzite" east of Churchill
12 11. Slabs of jointed bedrock frost-heaved into blisters
12 12. Felsenmeer
14 13. Sand content of the upper till sheet
15 14. The carbonate dispersal train in northern Manitoba
16 15. Surface character of the bouldery till unit
16 16. Grain sizes for Keewatin and Hudson tills
16 17A. Ribbed moraine landscape
17 17B. Gradation from transverse to longitudinal glacial bedforms
20 18A. Crevasse fillings surrounded by ribbed moraine
21 18B. Ground view of ridges showing their orthogonal geometry
22 19. Sedimentary facies associated with glaciolacustrine deposition
23 20. Iceberg scour marks
26 21. Thick sphagnun and woody peat deposits
27 22. Ice wedge polygons in tundra peat
27 23. Small palsa in grassy fen near Churchill
28 24. Coalesced peat plateaux and surrounding fenlands
29 25. Stratigraphic transects across northeastern Manitoba
30 26. Location of sections used to compile the stratigraphic record
31 27. Sediment sequences of northeastern Manitoba
32 28. Sand, organic detritus, and peat at Flamborough Head
36 29. Correlation of lithostratigraphic units across the Hudson Bay lowlands
38 30. Ice flow indicators
39 31. Pre-Wisconsin and Wisconsin glaciations in northern Manitoba
41 32. Pattern of ice retreat and expansion of Lake Agassiz
43 33. Area covered by Lake Agassiz in northern Manitoba
45 34. Areas indundated by Tyrrell Sea
48 35. Emergence curves for northeastern Manitoba
49 36. Raised beach berms near Cape Churchill
51 37. Longitudinal profiles and terrace levels, Churchill River
52 38. Stages of downcutting preserved in terraces and abandoned channels of Limestone Rapids
53 39. Distribution of permafrost
54 40. Mean annual ground temperatures for Churchill
55 41. Seasonal progression of thawing in peat
56 42. Ice wedge troughs

56 | 43. Stages in the development of thermokarst ponds
57 | 44. Large lakes in polygonal peatlands
58 | 45. Heaved rock panels at Churchill airport
59 | 46. Tripole support structures for hydro lines
59 | 47. Leaching of frozen and unfrozen, calcareous soils
62 | 48. Base metal, uranium, and gold anomalies in northeastern Manitoba
63 | 49. Base metal and uranium values

GLACIAL AND ENVIRONMENTAL GEOLOGY OF NORTHEASTERN MANITOBA

Abstract

Quaternary deposits in northeastern Manitoba are related to pre-Wisconsin and Wisconsin glaciations, the Sangamon Interglaciation, and postglacial lakes and seas. During the Wisconsin Glaciation, the map area was continually glaciated by Laurentide ice from two centres of outflow. Keewatin ice flowed southward and deposited a sandy to bouldery granitic till sheet, the surface of which is divided into belts of rib moraine and crevasse fillings. A second ice mass, centred over Hudson Bay, flowed westwards and deposited several silty calcareous till sheets, the uppermost of which is gently ridged by grounding-line moraines. The position of convergence of the two ice masses varied during the course of glaciation. A major segmented interlobate kame moraine, which was deposited largely during deglaciation, marks the final confluence.

Lake Agassiz covered the area vacated by the receding glaciers and persisted as long as ice sheets blocked drainage into Hudson Bay. Turbidite sands and varved or massive clays deposited into this water body cover the southern part of the region. Hudson ice disintegrated suddenly about 7800 (or 8000) BP, and the glacioisostatic Tyrrell Sea flooded areas below 180 m elevation; the land continues to emerge at a rate of 40 cm per century. A major raised beach, formed about 7200 BP, constitutes a major aggregate deposit.

Icy muskeg forms the terrain south of Seal River. Frost-riving of bedrock and aggradation or degradation of ground ice are current periglacial processes. Areas east of the Great Beach lie within the zone of continuous permafrost; those to the west lie in discontinuous permafrost. Because ground temperatures are near 0°C, the region is extremely sensitive to climatic or man-induced changes in thermal regime: a small change in ground temperature can produce major terrain disturbances. Permafrost has also limited the buffering capacity of the soils to counteract the effects of acid rain.

The surface till sheet has anomalously high concentrations of uranium north of Seal River and interesting gold associations near Great Island.

Résumé

Dans le nord-est du Manitoba, les dépôts quaternaires sont associés aux glaciations pré-wisconsiniennes et wisconsinienne, à l'Interglaciaire sangamonien et aux lacs et mers postglaciaires. Au cours de la Glaciation wisconsinienne, l'inlandsis laurentidien a recouvert en continuité la région cartographique à partir de deux centres d'écoulement. Les glaces du Keewatin se sont écoulées vers le sud et ont déposé une nappe de till granitique, sableux ou blocailleux, dont la surface se divise en zones de moraine côtelée et de remplissages de crevasse. Une deuxième masse de glace, centrée sur la baie d'Hudson, s'est écoulée vers l'ouest et a déposé plusieurs nappes de till calcaro-silteux; la surface de la nappe supérieure présente des moraines de limite d'ancrage doucement ondulées. La zone de convergence des deux masses glaciaires s'est déplacée tout au long de la glaciation. Une importante moraine de kame interlobaire segmentée, mise en place en grande partie au cours de la déglaciation, délimite la zone de confluence finale.

Le lac glaciaire Agassiz, qui a envahi la région suivant le recul des glaces, a persisté aussi longtemps que les nappes glaciaires ont obstrué le drainage dans la baie d'Hudson. Des sables turbiditiques et des argiles varvées ou massives accumulés dans ce lac recouvrent la partie sud de la région. Les glaces de la baie d'Hudson se sont désagrégées brusquement il y a environ 7 800 (ou 8 000) ans, et la mer glacio-isostatique de Tyrrell a inondé les régions qui se trouvaient à une altitude inférieure à 180 m. L'émersion des terres se poursuit aujourd'hui à un rythme de 40 cm/siècle. Une importante plage soulevée, qui s'est formée il y a environ 7 200 ans, constitue une source majeure d'agrégats.

Le territoire au sud de la rivière Seal se compose de muskeg glacé. La gélifraction du socle rocheux et l'accroissement ou la dégradation de la glace dans le sol sont des processus périglaciaires qui se poursuivent actuellement. Les régions à l'est de la grande plage (Great Beach) se situent dans la zone de pergélisol continu, et celles à l'ouest, dans la zone de pergélisol discontinu. Puisque la température du sol est presque 0 °C, la région est extrêmement sensible aux changements d'origine climatique ou anthropique que subit le régime thermique; toute petite fluctuation de la température du sol peut provoquer des perturbations majeures du terrain. En outre, la présence de pergélisol limite la capacité tampon des sols à compenser les effets des pluies acides.

La nappe de till superficielle présente des concentrations anormalement élevées d'uranium au nord de la rivière Seal et des associations aurifères intéressantes près de l'île Great.

SUMMARY

This study of the glacial geology and geomorphology of the Hudson Bay lowlands of Manitoba and adjacent parts of the Canadian Shield was prompted by a need for data on terrain and permafrost conditions related to engineering activity along a proposed pipeline and transport corridor. Understanding the glacial history is of importance because the region lies in the heart of the area covered by the Laurentide Ice Sheet, but at the confluence of two major ice masses within the larger ice sheet; the sediment record in this area is thus a key to understanding the structure and dynamics of the last ice age. The goals of the project were 1) to describe the geological and engineering character of terrain materials, and to determine their thermal characteristics; 2) to construct a map showing the distribution of Quaternary materials; 3) to explain the genesis and provenance of these deposits and to elucidate the geological history of the area; and 4) to document crustal warping, and sea level and coastal changes. Because the region lies along the boundary between discontinuous and continuous permafrost, special attention is also given to permafrost conditions and periglacial processes.

Surface materials. About 75% of the area is mantled by a blanket of peat. The character of the geological materials was determined by an extensive coring program, and by the examination of river bank sections. Bedrock outcrop is scarce, but Precambrian granitic and gneissic rocks underlie the northern and western part of the map area. Much of the crystalline rock is frost shattered into large blocks, and felsenmeer is a major landform north of Seal River. Paleozoic outcrop is exposed along the coast and occurs in section as far inland as Bad Cache Rapids on Churchill River. There are two main types of till. Sandy or bouldery granitic till deriving from Shield terrain is present in areas crossed by ice of Keewatin provenance; silty calcareous till deriving from the Paleozoic limestone is the main till type in areas crossed by Hudson and Labradorean ice. Keewatin till is exposed at the surface north of Seal River. The landforms there are primarily rib moraine grading to fluted till plains, interspersed with crevasse fillings. Hudson/Labradorean till forms the uppermost till sheet in the rest of the study area, although it is commonly overlain by postglacial

SOMMAIRE

La présente étude de la géologie glaciaire et de la géomorphologie des basses terres de la baie d'Hudson, au Manitoba, et des parties contiguës du Bouclier canadien a été entreprise en vue d'obtenir des données sur les facteurs topographiques et le pergélisol en vue des travaux techniques qui seraient menés le long du tracé prévu d'un pipeline et d'une ligne de transport d'énergie. Il est important de comprendre l'histoire glaciaire de la région, car cette dernière se trouve non seulement au coeur de la zone auparavant recouverte par l'inlandsis laurentidien, mais aussi à la confluence de deux grandes masses de glace qui se trouvaient au sein de l'inlandsis. L'étude des sédiments de la région permet donc de mieux comprendre la structure et la dynamique de la dernière époque glaciaire. Le projet avait pour objets (1) de décrire la nature géologique et technique des matériaux terrestres et de déterminer leurs caractéristiques thermiques, (2) de préparer une carte de la répartition des matériaux quaternaires, (3) d'expliquer la genèse et la provenance de ces dépôts et de reconstituer l'histoire géologique de la région et (4) de documenter le gauchissement de la croûte, les changements survenus le long de la côte et les fluctuations du niveau marin. Puisque la région se situe sur la limite entre le pergélisol continu et le pergélisol discontinu, on a accordé une attention particulière au pergélisol et aux processus périglaciaires.

Matériaux en surface. Une nappe de tourbe couvre environ 75 % de la région. La nature des matériaux géologiques a été déterminée grâce à un programme détaillé de carottage et à l'examen de coupes le long des cours d'eau. Les affleurements du socle rocheux sont rares, mais des roches granitiques et gneissiques du Précambrien reposent sous la surface dans le nord et l'ouest de la région cartographique. Les roches cristallines sont en grande partie gélifractées en blocs, et les champs de blocs constituent une importante forme de relief au nord de la rivière Seal. Des roches paléozoïques affleurent le long de la côte et se présentent dans des coupes aussi loin à l'intérieur des terres que les rapides Cache Creek, sur le fleuve Churchill. On retrouve deux grandes catégories de till. Du till granitique sableux ou blocailleux dérivé du Bouclier se rencontre dans les régions que couvraient auparavant les glaces du Keewatin; un till calcaro-silteux dérivé de calcaire paléozoïque constitue le till principal dans les régions anciennement couvertes par les glaces d'Hudson et du Labrador. Le till de Keewatin affleure au nord de la rivière Seal. À cet endroit, les principales formes de relief sont des moraines côtelées qui se transforment progressivement en plaines de till cannelées, parsemées de remplissages de crevasses. Le till déposé par les glaces d'Hudson et du Labrador constitue la nappe de till supérieure ailleurs dans la région à l'étude, bien qu'elle soit souvent recouverte de dépôts

deposits, so that there is little surface expression. The silty till can be separated into five separate sheets, each marking a different advance of ice. The landforms associated with silty till are plains of low relief, and broad, undulating ridges which are thought to be lift-off moraines. Clayey glaciolacustrine deposits cover till in the southwest quadrant of the study area, where ice recession occurred against a major glacial lake. These can be separated into coarse diamictic ice proximal facies, and varved and massive distal facies. The surface of the old lake plain is criss-crossed by iceberg scour marks. An offlap coarsening upwards sequence of marine sediments consisting of stony pelite, pelite, silt, and beach ridge sand occupies areas below an elevation of 140-180 m and indicates areas covered by the glacioisostatic Tyrrell Sea. Partly frozen peat more than 2 m thick mantles much of the study area. In discontinuous permafrost the main peat type is forested bog interspersed with thermokarst ponds. In continuous permafost the peat derives from sphagnum and heathland vegetation, and the terrain is dissected by large ice-wedge polygons.

Stratigraphic record and glacial history. River exposures reveal a sequence of till sheets separated by fluvial, lacustrine, and organic units. They record the interplay between the Keewatin and Labrador/Hudson ice masses over several glaciations and interglacial intervals. The sequence, from oldest to youngest is saprolite, two old tills, interglacial beds, a set of olive-grey sandy and silty tills separated by sand beds, brown till grading to glaciolacustrine silt (in places overridden by till), and marine and fluvial sediments. The oldest till indicates that Keewatin ice once covered the entire area. The next till up, the Amery till, was left by a major advance of Labradorean ice which covered the southern two-thirds of the region but did not cover the northermost part. The overlying organic beds and fluvial gravels were deposited during the Sangamon Interglaciation. The type and distribution of deposits indicate that Hudson Bay was free of glacier ice, and that the interglaciation began with a high level sea which subsequently regressed to a level lower than present sea level. Pollen profiles, wood species, and animal remains indicate that there was an early cool tundra environment, followed by a period when the climate and treeline position were similar to present, a period when climate was probably warmer than present and warm temperature foraminifera lived in Hudson Bay, and a final return to cool tundra conditions. A well developed soil formed during the interglaciation. The distribution of various tills of the Wisconsin Glaciation and interfingering sand beds indicate that both Keewatin and Labradorean/Hudson ice occupied northeastern Manitoba, and that the relative vigour and position of convergence of the two ice masses changed during the course of that glaciation. The shifting location of the convergence zone is marked in sections by unfossiliferous sandy beds laid down between till sheets by subglacial meltwater, and at the surface by a large interlobate kame moraine called the

postglaciaires, de sorte qu'elle n'affleure que rarement. Le till silteux se subdivise en cinq nappes, chacune marquant une avancée distincte des glaces. Les formes de relief associées au till silteux sont des plaines à relief doux et des crêtes larges et ondulées qui pourraient être des moraines de désancrage. Des dépôts glaciolacustres argileux couvrent le till dans le quart sud-ouest de la région à l'étude, là où la glace a reculé contre un important lac glaciaire. Ces dépôts comportent un faciès diamictique, grossier, juxtaglaciaire, et un faciès distal, massif et varvé. La surface de l'ancienne plaine lacustre est parsemée de marques d'affouillement laissées par des icebergs. Une séquence de recouvrement en retrait de sédiments marins à granulométrie inverse, composée de pélite pierreuse, de pélite, de silt et de sable de levées de plage se rencontre à une altitude inférieure à entre 140 et 180 m; sa présence indique que la mer glacio-isostatique de Tyrrell a inondé ces régions. De la tourbe partiellement gelée, dont l'épaisseur dépasse 2 m, recouvre une bonne partie de la région à l'étude. Dans les zones de pergélisol discontinu, elle se rencontre principalement dans des tourbières boisées, parsemées d'étangs thermokarstiques. Dans les zones de pergélisol continu, la tourbe est dérivée de sphaignes et de plantes éricacées, et le terrain est disséqué en grands polygones de toundra.

Stratigraphie et histoire glaciaire. Les affleurements trouvés le long de cours d'eau révèlent la présence d'une séquence de nappes de till que séparent des unités fluviatiles, lacustres et organiques. Elles témoignent du jeu des glaces du Keewatin, du Labrador et d'Hudson au cours de plusieurs intervalles glaciaires et interglaciaires. La séquence comporte les sédiments suivants, qui sont donnés en âge décroissant : de la saprolite, deux vieux tills, des lits interglaciaires, une série de tills sableux et silteux de couleur gris olive que séparent des lits de sable, du till brun qui passe progressivement à du silt glaciolacustre (par endroits recouvert de till) et des sédiments marins et fluviatiles. Le till le plus vieux révèle que les glaces du Keewatin avaient occupé toute la région. Le till suivant, celui d'Amery, a été mis en place au cours d'une avancée majeure des glaces du Labrador, qui ont couvert les deux tiers sud de la région mais non pas l'extrême nord. Les lits organiques et graviers fluviatiles susjacents se sont accumulés durant l'Interglaciaire sangamonien. La nature des dépôts et leur répartition indiquent que la baie d'Hudson n'a pas été englacée et que le niveau marin était élevé au début de l'interglaciaire puis a baissé pour atteindre un niveau inférieur à celui d'aujourd'hui. Les diagrammes polliniques, les essences forestières et les restes d'animaux attestent l'existence premièrement d'un milieu de toundra frais, suivi d'une période pendant laquelle le climat et la limite supérieure des arbres étaient semblables à ceux d'aujourd'hui, puis d'une période vraisemblablement plus chaude que la période actuelle, lorsque des foraminifères de climat chaud vivaient dans la baie d'Hudson, et enfin d'un retour à un milieu de toundra frais. Un sol bien développé s'est formé au cours de l'interglaciaire. La répartition de divers tills de la Glaciation wisconsinienne et des lits de sable interdigités indique que les glaces du Keewatin, du Labrador et d'Hudson ont occupé le nord-est du Manitoba et que la vigueur relative et la position du point de convergence des deux masses de glace ont changé au cours de cette glaciation. Des lits sableux non fossilifères déposés entre les nappes de till dans les coupes et une importante moraine de kame interlobaire, appelée «moraine de Burntwood-Knife», trouvée en surface, marquent les différentes positions de la zone de convergence. Des fossiles trouvés dans le till près du lac Tadoule

Burntwood-Knife Moraine. Fossils in the till near Tadoule Lake suggest that Hudson ice reached that far west, but an overlying sandy till sheet indicates that Keewatin ice later flowed southwards into the Hudson domain. The uppermost brown till sheet, which grades into waterlaid till and glaciolacustrine clay, was deposited as Hudson ice receded against Lake Agassiz. Ice marginal surges into the lake are evidenced by a clayey till composed of disrupted varves, and by spindle form ridges on the surface. During ice recession, Hudson ice flow continued to be active, while the Keewatin ice mass stagnated. Dates on marine shells indicate that the Hudson ice mass disintegrated rapidly about 7800-8000 years ago, and that the Tyrrell Sea reached more than 200 km inland from the present coast. The marine emergence record, together with terrace development along Churchill River, suggests that the sea regressed steadily. The present rate of emergence at Churchill is about 40 cm/century. The rate of emergence is greater in the northern part of the study area than around Nelson River in the south as a result of different degrees and timing of glacial unloading, and restrained rebound beneath Lake Agassiz. Postglacial river development and pollen records indicate a series of warm and cooler periods throughout the Holocene. About 6000 years ago, treeline was about 300 km north of its present position.

Economic considerations. The main economic aspects include land use concerns involving natural and man-induced changes to the thermal regime. The region is particularly sensitive because soil temperatures are just below freezing: small changes in the thermal regime can therefore cause freezing or melting of ground ice. The distribution of discontinuous and continuous permafrost has been mapped, and the deepest permafrost appears to be about 60 m thick. At present, seasonal surface thawing does not extend through dry peat into the mineral substrate, but penetrates through wet peat into the subsoil in areas of continuous permafrost. In peatlands, ice contents average about 30% of the dry soil weight; they decrease below a depth of about 3 m. The main engineering problems are heave and subsidence caused by ground ice, liquefaction of soils, seasonal earth churning and solifluction, and frost heave of bedrock. Massive rock panels are actively frost-heaved in the vicinity of Churchill airport. Studies on the buffering capacity of the soil against the effects of acid rain indicate that the calcareous tills, which should theoretically be good buffers, have already been leached considerably. Aggregate sources are limited to a few eskers and shallow beach ridge complexes. Lastly, geochemical analyses of till and other sediments indicate high uranium values in the Caribou River area, and elevated gold and arsenic concentrations in the volcanic complex along Seal River near Great Island.

portent à croire que les glaces d'Hudson se sont avancées vers l'ouest jusqu'au lac, tandis que la présence d'une nappe susjacente de till sableux indique que plus tard, les glaces du Keewatin se sont écoulées vers le sud jusque dans le domaine d'Hudson. La nappe supérieure de till brun se transforme progressivement en till sous-aquatique et en argile glaciolacustre; sa mise en place date du moment où les glaces d'Hudson ont reculé contre le lac glaciaire Agassiz. La présence d'un till argileux composé de varves perturbées et, en surface, de crêtes fusiformes, indique que la marge glaciaire s'est avancée en crue dans le lac. Au cours du retrait glaciaire, les glaces d'Hudson sont demeurées actives tandis que les glaces du Keewatin ont stagné. La datation de coquilles marines indique que les glaces d'Hudson se sont désagrégées rapidement il y a environ 7 800 à 8 000 ans, et que la mer de Tyrrell s'est avancée à plus de 200 km à l'intérieur de la côte actuelle. Les données sur l'émersion et la formation de terrasses le long du fleuve Churchill portent à croire que la régression marine s,est poursuivie sans interruption. Le taux d'émersion est actuellement d'environ 40 cm/siècle à Churchill. Il est plus rapide dans le nord de la région à l'étude qu'à proximité du fleuve Nelson au sud, car le rajustement isostatique de la croûte s'est poursuivi à des degrés et des moments différents et que le rebondissement de la croûte a été limité sous le lac glaciaire Agassiz. Le développement postglaciaire de cours d'eau et les données polliniques indiquent qu'il y a eu une série d'intervalles chauds et d'intervalles plus frais tout au long de l'Holocène. Il y a environ 6 000 ans, la limite supérieure des arbres se trouvait environ 300 km au nord de sa position actuelle.

Questions économiques. Les principales questions économiques ont trait à l'utilisation des terres, notamment aux changements naturels et anthropiques que subit le régime thermique. La région est particulièrement sensible à ces changements, car les températures du sol sont juste au-dessous du point de congélation : par conséquent, tout changement qui se produit dans le régime thermique peut provoquer le gel ou le dégel de la glace dans le sol. On a cartographié la répartition du pergélisol continu et discontinu, et le pergélisol le plus profond semble avoir une épaisseur d'environ 60 m. Actuellement, le dégel saisonnier ne traverse pas la tourbe sèche pour atteindre le substratum minéral; toutefois, il pénètre la tourbe mouillée jusque dans le sous-sol dans les zones de pergélisol continu. Dans les tourbières, la teneur en glace atteint en moyenne 30 % du poids sec du sol; elle baisse à une profondeur de plus d'environ 3 m. Les principaux problèmes techniques sont le soulèvement et l'affaissement provoqués par la glace dans le sol, la liquéfaction des sols, le brassage et la solifuxion saisonniers du sol et le soulèvement gélival du socle rocheux. Le gel soulève des blocs rocheux massifs près de l'aéroport de Churchill. Les études de la capacité du sol à compenser les effets des pluies acides indiquent que les tills calcaires qui, en théorie, aurait une capacité tampon élevée, ont déjà subi un lessivage considérable. Les seules sources d'agrégats sont quelques eskers et complexes de levées de plage peu profondes. Enfin, les analyses géochimiques des tills et d'autres sédiments indiquent une teneur élevée en uranium dans la région de la rivière Cariboo, et des teneurs élevées en or et en arsenic dans le complexe volcanique qui longe la rivière Seal, près de l'île Great.

INTRODUCTION

Objectives

This report and Map 1617A result from an investigation of the Quaternary geology and geomorphology of part of northeastern Manitoba (Fig. 1). This region includes vast tracts of frozen peatland that form the Hudson Bay lowlands, adjacent forested swampy regions of the Canadian Shield, and the rubbly barren plains north of the treeline. The report area lies between the estuary of Nelson River and the boundary with Northwest Territories; it is bordered on the east by Hudson Bay, and on the west by longitude 96°W and covers about 48 000 km^2.

Early in this century, Tyrrell (1913a) recognized the need to inventory the features and deposits of the region and to understand the processes that formed them; but few studies were done because of the difficulty of obtaining geological information in this peat-mantled terrain. The present study was first prompted by the need for data on terrain and permafrost conditions related to engineering activity along a proposed gas pipeline corridor and later for land use planning in general. In this area of sparse outcrop, understanding the directions of glacial transport was also needed for drift prospecting and mineral exploration. In addition, understanding the glacial history is of special interest because the region lies in the heart of the former North American ice sheet and along the zone of confluence of two major ice masses, having different centres and styles of flow, within the larger ice sheet complex. The region forms a key to understanding the structure and dynamics of the North American ice sheet complex.

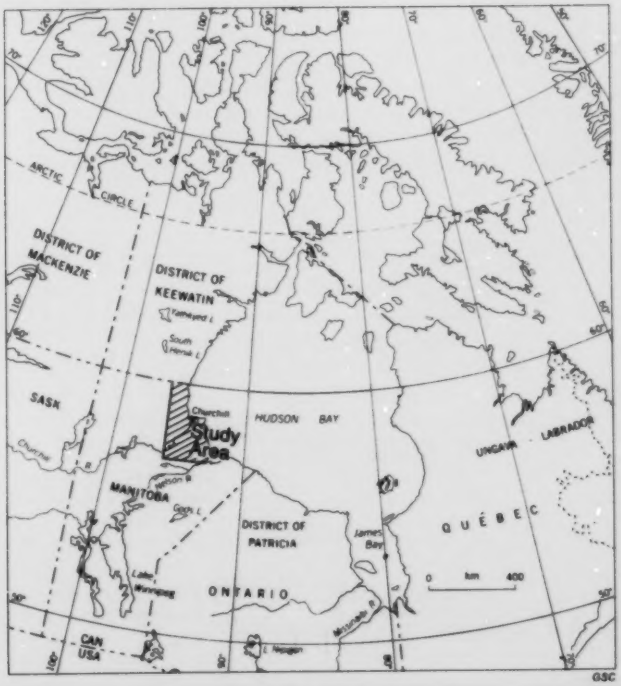


Figure 1. Location of the study area.

Thus the goals of the project were 1) to describe the physical character of unconsolidated materials, including their geological nature, their engineering properties, and their sensitivity to seasonal and long-term temperature changes; 2) to construct a map showing the distribution of surface deposits; 3) to explain the genesis and provenance of these deposits and elucidate the geological history of the region; and 4) to document crustal movements, particularly sea level changes.

Field work

Field work was carried out in 1977, 1978, 1979, and 1985. Areal mapping was initiated by airphoto interpretation and was subsequently checked by ground surveys. Ground investigations were made by helicopter traverses, supplemented by short foot traverses from landing sites. In total, about 600 ground sites were examined. North of Seal River, mapping was accomplished by airphoto interpretation, by helicopter and ground traverses, and by examining materials and sedimentary structures in hand-dug pits. That survey is well controlled using the above methods.

Much of the southern half of the area, however, is mantled by extensive tracts of open, frozen organic terrain or by forested bog. Both airphoto interpretation and ground mapping of the underlying inorganic materials were hindered by these conditions. Helicopter landings, and hence field investigations, were restricted to small openings in the bogs, or to treeless sites with a thick frozen peat cover. The extensive swamp limited traversing on foot. In unfrozen terrain, pits were dug by hand to determine the character of the deposits; in frozen ground and thick organic deposits observations to 3 m were made and mineral soil samples were taken using manual or power-driven coring augers. The aerial mapping in these areas, based on spot sites and a few river sections is thus only moderately controlled. Because of restricted access, ground data are especially sparse in the Rocket Range, which covers all areas east of longitude 94°W beyond the road network at Churchill. Stratigraphic mapping was accomplished by observing the lateral areal juxtaposition of materials and the superposition of units exposed in river bank sections.

Scope of the report

This report describes the nature and distribution of surficial materials and offers an interpretation of their mode of formation. Accompanying Map 1617A portrays eight genetic classes of surficial materials of northeastern Manitoba and forms the basis of this report. The next major section of this report describes the physical properties of materials and their landforms, along with laboratory data on texture and composition. A stratigraphic framework follows. The Quaternary history section provides an interpretation of ice flow centres, glacial events, and the inundation of the region by postglacial lakes and seas. The final section deals with topics of particular interest in drift prospecting, hazards, terrain sensitivity, and resource development.

Surficial geology maps of the study area exist at a scale of 1:250 000 (Dredge and Nixon, 1981a-e). Many topical reports have been published, dealing with the evolution of peatlands (Dredge, 1979) and their thermal properties and sensitivity (Dredge and Nixon, 1979), trace elements and gold in till (Dredge, 1982b, 1983a,b; Dredge and Nielsen, 1986), aggregate sources (Dredge and Nixon, 1980), soil leaching and buffering (Dredge, 1981b, and 1988a,b), and some aspects of glacial history (Dredge, 1982a, 1988b; Dredge and Nielsen, 1985, 1987a,b; Dredge and Cowan,1989; Dredge et al., 1990). The Churchill region has been studied by Paradis (1980) as part of this project.

Previous work

Bedrock

Bell (1880), Tyrrell (1898a,b), and Alcock (1916) each commented on the nature of the bedrock in this region, but more than half a century elapsed before systematic mapping began. Davidson (1966) produced a bedrock map for the area north of 59°N, and soon after, Sanford et al. (1968) and Bostock (1969) mapped the Paleozoic and Precambrian bedrock in the remaining area to the south. Schledewitz (1977a,b, 1986) has since remapped the Precambrian area in greater detail.

Glacial deposits

Although Bell (1879, 1880) made passing reference to glacial deposits in this area, it was Tyrrell (1894, 1898a,b, 1913a,b) who recorded the first observations related to the glacial history of the area west of Hudson Bay. From striations measured he suggested that there must have been three major "gathering grounds", or centres of glacial inception and outflow, for the continental glaciers. One centre was in central District of Keewatin (called "Keewatin"), another southwest of Hudson Bay in the District of Patricia (called "Patrician"), and a third in what was then Labrador, now Nouveau Quebec (called "Labradorean"). The Keewatin and Patrician centres concern this study region, and evidence presented in this report amplifies and substantially confirms Tyrrell's ideas. Tyrrell (1898a) noted the generally stony till that occurs along the coastal plain, described occurrences of frost shattered rock, identified three successive sets of striae at Churchill, defined his concept of the "Keewatin ice centre", recognized its influence on the study area, and placed the limit of postglacial marine submergence at 500 to 600 feet (150 to 180 m) in the Owl River area; in his 1894 report, he placed it at 400 feet (120 m). Tyrrell also commented on the height above present high tide of the mooring rings at Fort Churchill, emplaced by Samuel Hearne in 1758, and concluded that the present rate of emergence might be about 0.4 cm/year.

O'Sullivan (1907) described the terrain along the Little Churchill-Deer River canoe route. He commented on the clayey overburden, extensive peat cover, and occurrence of ground ice. McInnes (1913) provided information about the Churchill River basin, recognized a south-southwest and subsequent westerly glacial flow over the area, and noted marine fossils up to an elevation of 350 feet. (106 m).

More recently, Taylor (1961) discovered and reported on subtill organics along Seal River. Ritchie (1962) made a landform and a vegetation map, at a scale of 1:1 000 000, for the entire area as part of a geobotanical study. His work was based on airphoto interpretation and three ground sites. Barnett (1970) examined tide gauge records at Churchill and found the present rate of emergence to be 0.4 cm/year. Wagner (1967) described fossil marine assemblages and determined their radiocarbon ages. Craig (1969) established a minimum age of 7300 years for the Tyrrell Sea episode and determined marine limit to range from about 400 feet (120 m) near Weir River to 610 feet (185 m) near Caribou Lake; he presented an emergence curve for Churchill for the last 3000 years.

This project is the first systematic attempt to map the Quaternary deposits of the area, to determine the physical character of these materials, and, based on them, to offer an interpretation of the glacial and postglacial history of the region. Short reports on thermal sensitivity of the peatlands, prediction of seasonal thaw depths in permafrost terrain, carbonate leaching and buffering capacity of the soils, a sand and gravel inventory, relict iceberg furrow marks, the stratigraphic record and early glacial history, carbonate dispersal patterns, ice recessional patterns, evolution of Lake Agassiz, as well as till geochemistry have been published by the authors as part of this project. In addition, Nielsen and Young (1981), Nielsen and Kroker (1982), Klassen (1983, 1986), and Nielsen (1987) have contributed to the understanding of the glacial history and till geochemistry of this map area.

Bedrock geology

Precambrian intrusives, metasediments, and volcanics form the basement rocks of northeastern Manitoba (Schledewitz, 1986). The rock types of greatest areal extent are monzonite, granodiorite, charnockite, tonalite, and granitoid gneisses. Metavolcanic rocks and related metasediments underlie the Seal River area, and related quartzites protrude through the overlying cover

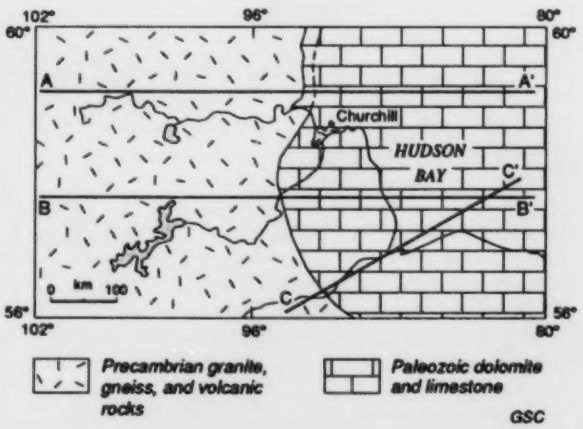


Figure 2. Bedrock geology and location of physiographic transects shown on Figure 3.

of Paleozoic sediments at Churchill. The Precambrian rocks belong to the Churchill structural province, which has an overall east-trending structural grain.

Silurian and Ordovician sedimentary rocks unconformably overlie Precambrian rocks in the southeastern part of the area (Fig. 2). They consist of a basal sandstone member overlain by limestone, bioclastic limestone, and dolomite (Sanford et al., 1968). The strata dip gently northeastwards, towards Hudson Bay, with a dip varying between 2 to 7 m/km, except near Nelson River, where they dip more steeply into a previously existing valley. Paleozoic rocks lie at the surface on the tidal flats along the present coast and are exposed in sections along Churchill River. In other areas they are overlain by up to 75 m of drift.

Cretaceous rocks have not been mapped in this region; however, reports of "lignite" (Williams, 1948) from a locality 56 km southwest of Churchill, the occurrence of black basal tills in the vicinity of Little Churchill River, and observations of shale clasts containing marine fossils (E. Nielsen, personal communication, 1986) in the oldest till

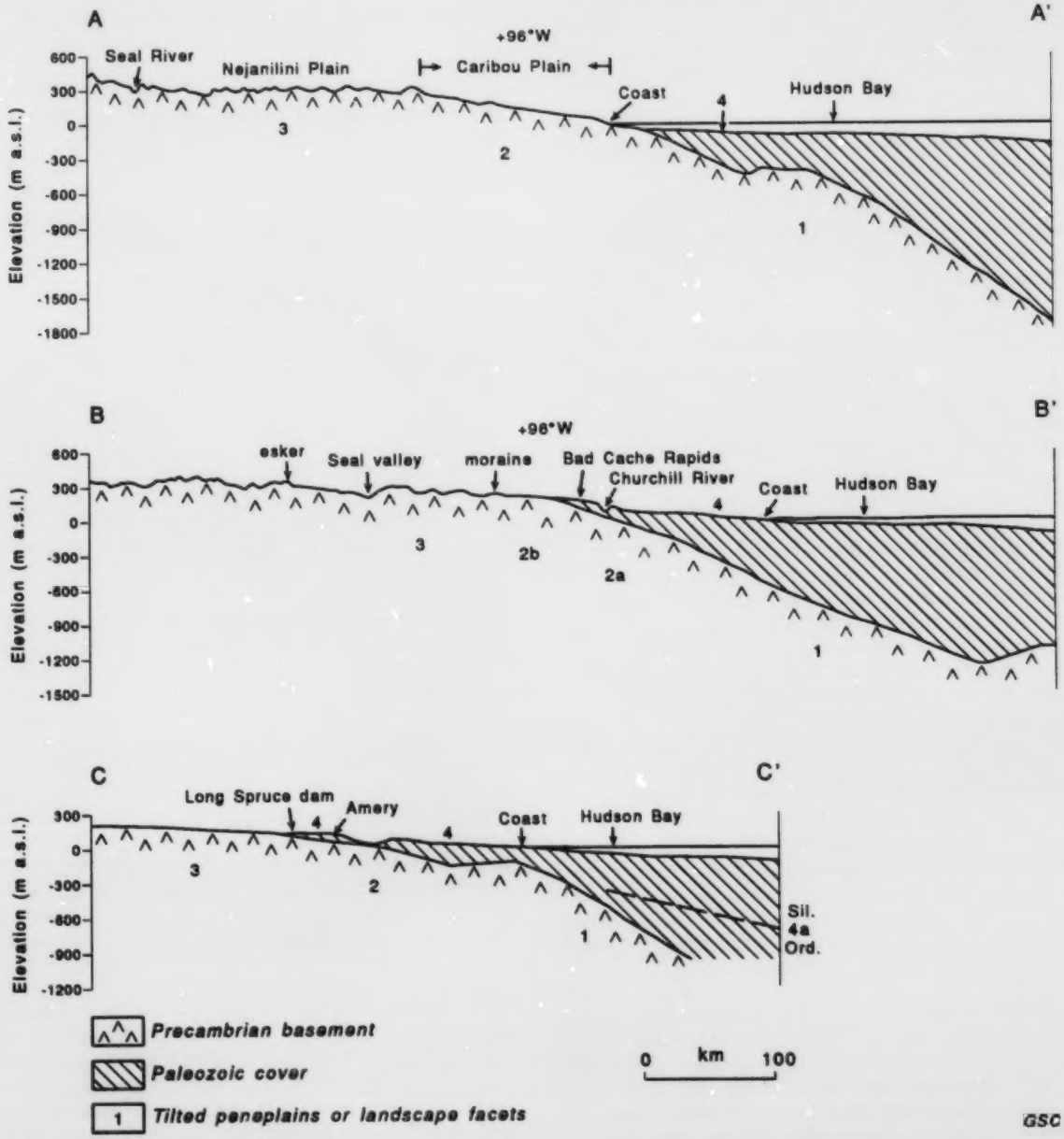


Figure 3. Physiographic transects across northern Manitoba show landscape facets, each of which may have been produced during an ancient period of peneplanation.

sheets in some localities suggest that a Cretaceous stratum may underlie the bog and till in the area south of Bradshaw lake.

Physiography

The entire area forms a uniform, gently sloping plain with subdued topographic features. The land rises gently from sea level at Hudson Bay to 250 m at 96°W and to 530 m at the Manitoba-Saskatchewan border, as shown on the topographic profiles in Figure 3. The topographic profiles, outcrop examination, bathymetric information, well data on basement depths, and seismic profiles (Hobson, 1969) suggest that the main elements of the present landscape comprise a series of relict, slightly tilted erosion surfaces of various ages, all of which predate the glacial epochs. The erosion surfaces are distinguished from each other by their different relief and slope. The present landscape may have evolved from three to five periods of peneplanation (Fig. 3).

The oldest surface (facet 1, Fig. 3), containing broad undulations, underlies and predates the deposition of Paleozoic rocks of Hudson Bay and dips towards the centre of Hudson Bay with a slope of 5 m/km. A second surface, resolved into two surfaces in some profiles, truncates and bevels the older surface. It is best preserved in the Caribou River area (Caribou plain, transect – A-A′ Fig. 3). The surface has a mature, regular profile and dips underneath Paleozoic rocks with a uniform slope of 2.5 m/km. It can be seen in section along the coast east of the town of Churchill, as an erosional unconformity between the Precambrian and Paleozoic rocks (Dredge and Nielsen, 1987a). Alcock (1920), Ambrose (1964), and Wright (1932) examined the character of this surface in other areas and noted that the gentle rolling relief extends beneath the Paleozoic rock. The Nelson River valley may have formed during this Precambrian phase of peneplanation, because the seismic profiles near Nelson River show that the Paleozoic strata dip steeply into what must have been a pre-existing valley. The remaining surfaces consist of the hills and plains of the northwestern Manitoba uplands and the truncated Paleozoic beds in Hudson Bay. Both surfaces have irregularities, including broad river valleys. The regional slope of both surfaces is 0.6 m/km. They are post-Devonian in age and the last surface may have developed during the Tertiary. The proto-Seal River developed during this phase, and its drainage basin included much of the present Churchill River watershed (Dredge et al., 1986). Although the two surfaces have fairly similar slopes they are separated by about 300 m elevation and thus may have developed during different episodes. The saprolites observed along North Knife River (Dredge et al., 1986) may have developed during the latter stage.

Although the primary elements of the landscape developed in pre-Quaternary time, many details of the present land surface have glacial and postglacial origins. Glaciers have scoured and freshened rock surfaces, removing the deeply altered regolith in most places. Glacial drift sheets mantle or mask the bedrock topography, creating a second-order relief consisting of glacial flutes, transverse ridges, and kame hills. Proglacial lake deposits and fine grained marine deposits have infilled the underlying topography and produced conditions favouring the development of extensive wetlands – the flat muskeg area of peatlands, disrupted drainage, and thermokarst lakes. Northeastern Manitoba can be subdivided into five landscape units on the basis of landforms, vegetation patterns, and drainage: the Caribou Plain, Hudson borderland, patterned peatland, the Great Beach and forested bog and fenland (Fig. 4).

The Caribou Plain (Fig. 5) forms the northern part of the study area, lies above treeline, and rises from sea level to 150 m. The main landscape components are felsenmeer, rock knobs, rib moraine, crevasse fillings, and lakes; the lakes can be subdivided into two types: (1) rock basin lakes, which reflect bedrock structure and have irregular outlines, and (2) elongated lakes, which occupy the depressions between morainal ribs. Except for a large till ridge 30 m high in the westernmost part of the area, local relief is about 5 m and is primarily created by the ribbed moraine. The ribbed moraine and intervening lakes are also responsible for the east-west surface fabric characteristic of this region. The positive relief features in this area are well drained.

The "Hudson borderland" region (Fig. 6) includes the uniform, low, very flat wetlands adjacent to Hudson Bay; the modern boulder-strewn tidal flat that extends far out into the bay at low tide; the flights of dry raised beach ridges that trend parallel to the coast; and the swampy distributaries of streams that enter Hudson Bay. A prominent bedrock ridge near Churchill and two large kames between Churchill and Cape Churchill also lie within the region but are not a typical part of it. A thin veneer of fen meadow and, in places, stringed fen or coalesced palsa mantle the mineral soil, which consists of marine silt, commonly frost churned with till and stony glaciomarine silt. Water covers the surface except for the beach ridges.

The patterned peat plateau (Fig. 7), which lies between 30 and 120 m a.s.l., is the most extensive physiographic unit. This unit comprises thick (>2 m) peat; ice wedges, which give the distinctive patterned aspect seen on airphotos; numerous thaw ponds, which lie completely within the peat; and a few larger shallow lakes (e.g., Fletcher Lake), whose bottoms lie on mineral soil. This unit lies within the zone of continuous permafrost. The predominant vegetation cover is a treeless lichen-heath tundra community. The surface of the peat, between ponds, commonly dries out in summer. Thaw depths rarely exceed 60 cm; below this depth the peat is ice rich. Peat has infilled all topographic irregularities in the mineral substrate. Local relief of 1 to 2 m is created by the melting of ground ice, particularly along and at the intersections of ice wedges.

The Great Beach (Fig. 8) is the prominent arcuate ridge that separates the patterned peat area from the forested bogs. In plan, the arc is concave westwards. This prominent feature is 170 km in length and varies between 100 and 250 m in width. It consists of multiple, well formed beach ridges and inter-ridge lagoons; its elevation rises gently from 122 m in the south to 140 m in the northwest, where it merges with a kame moraine.

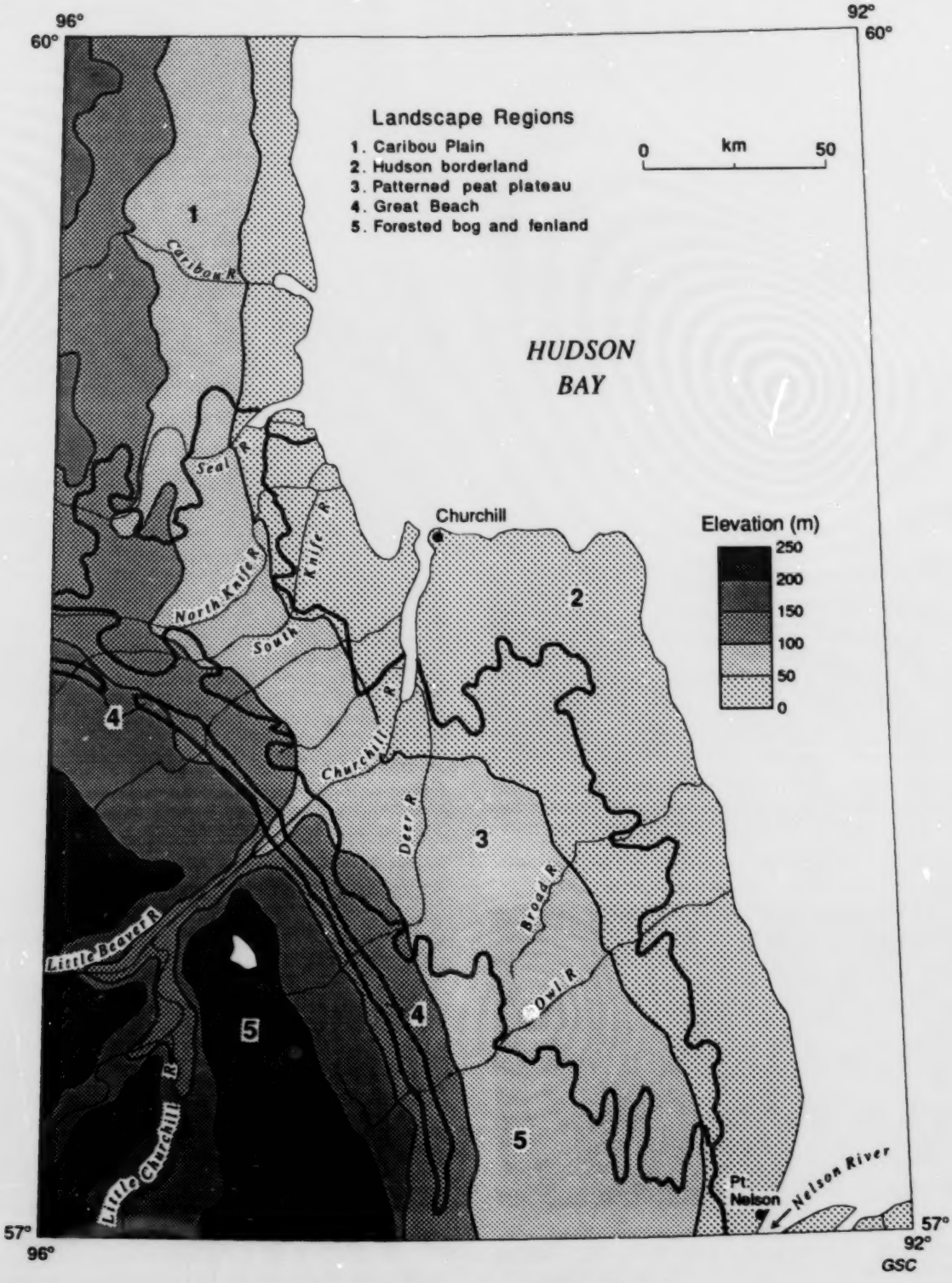


Figure 4. Landscape units of northeastern Manitoba.

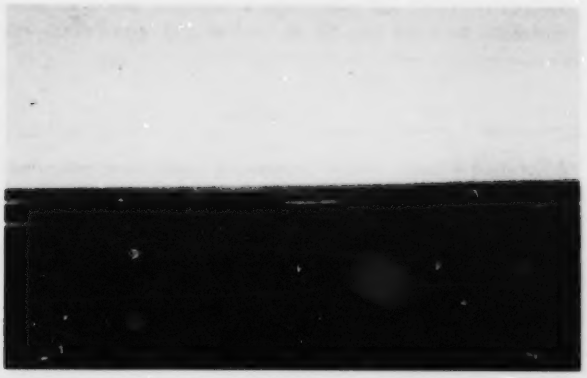


Figure 5. Caribou plains region, north of Seal River, showing extensive areas of frost-shattered rock. Small area in foreground is peat with ice-wedge polygons. Subarctic tundra vegetation consists of lichen cover on rocks and stunted spruce groves. (GSC 204036-A)

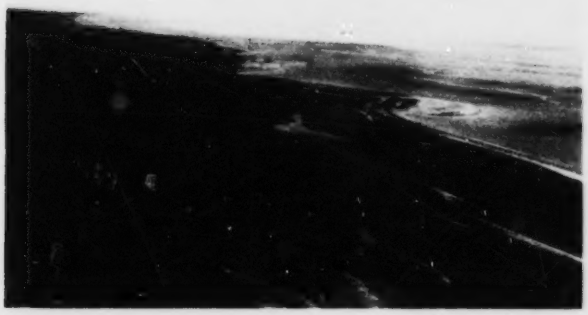


Figure 6. Hudson borderlands: sandy raised beaches, and wetlands underlain by blanket marine deposits. Hudson Bay is at the right of the photo. (GSC 204860-B)

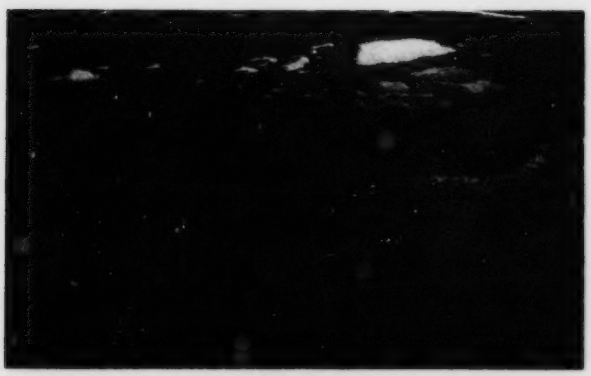


Figure 7. Patterned peat plateau: continuous wetlands consisting of thick sphagnum peat deposits containing ice-wedge polygons, interspersed with thermokarst ponds. The peat surface supports a lichen-heath vegetation. Stunted spruce borders the creek. Photo near Owl River with Hudson Bay Railway in background. (GSC 205283-K)

The forested bog and fenland (Fig. 9) lies between elevations of 120 and 250 m. Thick till sheets, which are overlain by glaciolacustrine deposits and capped by a mantle of peat, create the slightly undulating regional topography that characterizes the area. Broad, arcuate, elongated ridges may be moraines. This gently rolling land is dissected by the incised valleys of Churchill and Little Churchill rivers and by two prominent esker ridges trending southwest across this area. On airphotos the terrain appears riddled with thermokarst depressions, 2 to 4 m deep and generally occupied by open grassy fen. The surrounding higher areas or mounds are bogs, which are vegetated by spruce forest. This region also is poorly drained, although an incipient drainage network has developed. Lakes are common features, but unlike those within the peat plateau area, these bottom out in mineral soil. This region lies within the zone of discontinuous permafrost; bogs are commonly frozen and ice rich below a depth of 1 m, but permafrost is not present below all fens.

Figure 8. The Great Beach – a massive multiridged beach complex of spits and berms. Background shows forested bog with numerous fens. (GSC 204860-C)

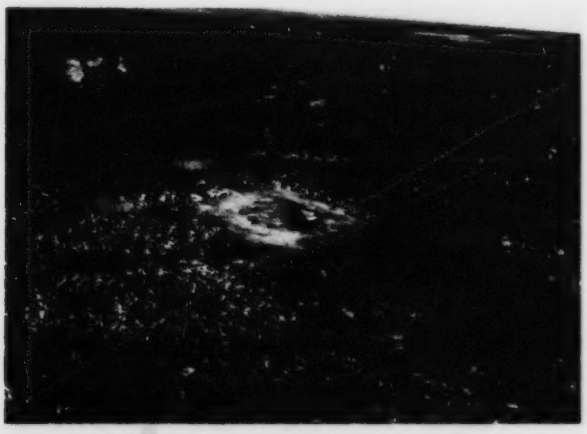


Figure 9. Forested bog with fens in thermokarst depressions. The forested bog areas are vegetated by spruce stands with a sphagnum-lichen understory. Fen areas are sedge peat, and dark areas are open water. Alders line the river. (GSC 203121-G)

Drainage

All rivers drain eastwards into Hudson Bay but many have long north-south reaches. Seal and Nelson rivers and some segments of Churchill River have ancient origins. The remainder postdate the last glaciation. Churchill River, with its rock-walled gorge, and the Little Beaver and Little Churchill tributaries, which are cut into drift, are deeply incised. North and South Knife rivers, also originating outside the region, cross it and are incised to a lesser degree. None of these through-flowing rivers has had much effect on the regional drainage. Drainage over most of the land surface is extremely poor and chaotic in pattern, partly because of the low relief, partly because of the frozen semipermeable condition of the subsoil created by high ice content in soil pores, and partly because of the impermeable clayey substrate. Owl, Deer, and Caribou rivers originate within the area, have shallow channels, and become swamps at their mouths. Extensive areas are covered with a myriad of small, seasonally interconnected lakes and ponds, or swampy areas. Some of these wet areas occupy rock basins or depressions in glacial drift, but others lie totally within the peat that mantles most of the region.

Climate

The southern part of the area lies within the boreal climatic region, and the northern in the subarctic. Climate is more rigorous near the coast than in areas farther inland. The mean annual air temperature at Churchill is -7.3°C; daily means range between 12°C for July and -28°C for January. The frost free period is 110 days. Precipitation averages 397 mm annually, of which 184 mm falls as snow. Prevailing winds are from the northwest in both winter and summer, at an average velocity of 22 km/h.

Many of the geomorphological features and the thick organic deposits, which are so extensive in this region, are directly related to present day climatic conditions: The summers are sufficiently warm and humid to produce large organic accumulations, and the climate is cold enough to prevent rapid decay; peat deposits are thick and widespread. Low annual temperatures and strong winds promote deep freezing; permafrost is prevalent, and the seasonal depth of thaw in many areas is only 40 to 60 cm. Frost cracks, ice wedges, and palsas are common features related to repeated melting and freezing of water in soils and to the aggradation of massive ice bodies; thermokarst depressions develop when these ice bodies melt. Seasonal or diurnal freezing also promotes frost churning of soils, as manifested by the prevalence of mudboils; and frost shattering of bedrock, manifested as rock blisters, heaved joint blocks, and rubbly rocky plains.

SURFICIAL MATERIALS

The distribution and character of surficial materials were determined by a combination of airphoto interpretation and ground observation. North of 59° latitude geological materials and map unit boundaries can easily be recognized on airphotos because they have distinctive shapes, topographic expression, surface reflectivity, or vegetative cover. In the southern half of the region, however, because peat mantles most inorganic deposits, materials were mapped and characterized from data obtained from augering and shallow drilling. Thus, except for beach ridges and eskers, the boundaries for these map units are only approximate.

Map 1617A shows the distribution of eight genetic classes of materials: rock outcrop, broken rock, till, glaciofluvial, glaciolacustrine, marine, fluvial, and organic deposits. The general distribution, physical nature, and topographic form of these materials are described here and, in some cases, the mode of origin or geological significance is discussed. Thick organic deposits, which cover extensive areas, are treated as a surficial material in the text and are shown on the inset to Map 1617A, but appear only as the swamp-symbol overlay on the main map, so that the principal inorganic material could also be portrayed. The various types of organic materials for this area are shown more precisely in Dredge and Nixon 1981 (a-e).

Additional geological units observed only in section are described in the section dealing with the *Stratigraphic record*.

*Bedrock outcrop (Ra, Rb)**

Coherent rock outcrop covers less than 0.5% of the region. Precambrian crystalline rock types are common in the northern part of the region, at Churchill, and along the bed of Churchill River farther south and west. Although true outcrop covers a very small percentage of the region, substantial areas north of Seal River have Precambrian rock near the surface. The intricate, angular configuration of lakes in these areas is a reflection of the bedrock structure. Paleozoic sedimentary rocks are exposed along parts of the coast and in North Knife, South Knife, and Churchill River valleys.

Glaciated Precambrian outcrop

The coherent Precambrian rocks, which are buff to pink in their unweathered state, consist of medium grained gneisses, monzonites, and granodiorite. Clusters of rounded knolls, each 2 to 3 m high, are common in the area west of Long Lake. Their surfaces are glacially scoured, but grooves are poorly defined (they appear as chip lines) and striations are rare. The rock surfaces are spalled and flaked, and weathered rinds up to 1 cm thick are common. Schledewitz (1977a) observed deeper weathering and noted that the rock surfaces were "rusty orange grading to a brown inner zone extending 5 to 10 cm into the rock".

A prominent bedrock ridge about 10 m high runs northeast from Holcroft Lake, 25 km west of Churchill, and then along the coast to a point 20 km east of Churchill. These rocks consist of grey, medium to fine grained protoquartzite. The rocks show signs of intense glacial action; ice moulded rock forms, oriented at 240°(SW), are common. These have rounded, abraded stoss sides on the northeast, and plucked lee

*map unit on Map 1617A

sides (Fig. 10). Both grooves and striae are abundant on the rock surfaces, particularly on north and east facing surfaces. The orientations of striae and grooves are highly variable but the most common trends are 180° and 220° to 240°. Crosscutting relationships indicate that the 240° striae were formed both before and after the 180° ones and that there was a late ice flow at 145° to 160°. In one place a chattermarked, weathered facet gives evidence of a very early flow at 310° to 325° or 130° to 145°.

Although much of the rock surface reflects the action of glaciers, frost heave has created two types of distinctive microrelief. Rock blisters (Fig. 11) protrude through the shallow overburden in areas where rock lies near the surface. These domal structures, roughly 4 m across and up to 2.5 m high consist of bedrock sheets (slabs) raised to form low mounds. Similar features in Northwest Territories have been reported by DiLabio (1978) and Dyke (1979), and in Quebec by Dionne (1983). Their occurrence is associated with excessive pore water pressures created during annual freeze-back (Dyke, 1979, 1981). They are limited to areas where the bedrock exhibits horizontal fracturing and where the water table is high. By the same processes, massive slabs or panels of Precambrian quartzite have been ejected as much as 3 m above the surrounding glaciated outcrop at the Churchill airport. These features have been well documented by Dyke (1984) and are discussed more fully under *Economic geology*.

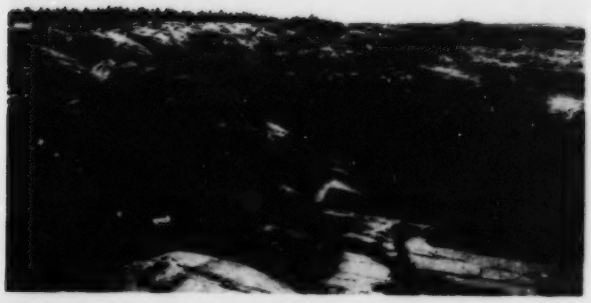


Figure 10. Roche moutonnée forms in Precambrian "quartzite" east of Churchill. Striated and polished stossed surfaces and plucked lee sides indicate ice flow from the north (right). Stunted spruce in the foreground show characteristic lobstick forms associated with high wind shear. (GSC 204036-K)

Figure 11. Slabs of jointed bedrock frost-heaved into blisters. Doming is caused by seasonal ice riving and by the build-up of excessive pore water pressures during freeze-back. (GSC 2-27-77)

Paleozoic outcrop

Flaggy, gently dipping buff limestone, dolomite, and calcareous mudstone of Silurian and Ordovician age lie along the shore between Churchill and the mouth of Owl River. The rocks form a gently sloping erosional platform exposed at low tide. Most of these rocks have fresh surfaces and are scoured regularly by sea ice. Limestone outcrop also forms the chasm between Limestone Rapids and Portage Chute on Churchill River; the walls in this part of the valley are vertical. Solution pipes were observed in several places. Limestone outliers were also noted beneath till in sections on North Knife River near the western boundary of the map area.

Broken rock, felsenmeer (1)

Broken rock, covering vast expanses between Seal River and Long Lake, and covering 3 to 4% of the total map area, is more prevalent than coherent bedrock outcrop. The rubble forms blockfields dissected by polygonal frost cracks.

The broken rock (Fig. 12) consists mainly of frost-shattered joint blocks derived from underlying bedrock; some erratic boulders are also present. Although in some places blocks appear to have been transported horizontally for short distances, in many others the rock has only been heaved vertically. The blocks are commonly quadrilateral in shape, measure 0.5 to 2 m on a side, and have angular edges. Heaved blocks are stacked about three deep. The largest interstices occur in the surface layer; the blocks are more closely spaced at depth and ultimately merge into ruptured, jointed bedrock. Perennial ground ice lies at the base of the uplifted blocks and in the underlying bedrock fissures.

Figure 12. Extensive areas of angular, frost-heaved bedrock blocks (felsenmeer) form the major rock unit in the region. (GSC 203121-R)

Individual rocks within the blockfields rarely have weathered rinds and carry no glacial markings. The uppermost blocks are lichen covered.

Although this terrain type is distinctive, it merges gradually with bouldery till (unit 2a), where recognizable erratics become more prevalent, a till matrix is present and the rubble is pushed into morainal ridges.

The age and origin of the broken rock are not clear. Frost shattering of joint blocks continues to enhance or create boulder fields at present, and presumably this process was active in the past. The fact that boulder fields merge into bouldery till suggests that at least some rubble was present prior to glaciation and was incorporated into the till. Rupturing of the bedrock into blocks could have been effected either (1) by frost-shattering prior to glaciation; (2) by crushing of the bedrock by the downward force of glaciers (Sugden, 1977 and 1978), in which case the area would have been in the central crushing zone of an ice sheet during part of the last glaciation; or (3) by both. We favour the first hypothesis because of the apparent lack of intermediate crushing sizes. Excavation to bedrock, however, may reveal matrix material finer than boulders that has migrated and accumulated at the rubble-bedrock contact; if this is the case, the second possibility will have to be given more consideration.

Till

Unsorted or poorly sorted glacial debris, deposited either beneath or at the front of moving glaciers or beneath ice shelves, is widespread in northeastern Manitoba. Till is extensively exposed in the north half of the map area and underlies relatively thin lacustrine and marine sediments in the south half. The northern till is generally thin (<5 m thick); the more southern till is stacked in sheets to thicknesses of more than 30 m.

The major factors controlling the texture and composition of till in this area are the nearby or subjacent rock types and direction of glacial transport. The two major till types in this region, derived from two contrasting source rocks were deposited by ice moving in two different directions. Sandy till (unit 2b) and related bouldery till (unit 2a), derived primarily from Precambrian Shield rocks, have a predominantly sandy matrix and consist of salic components. These tills were deposited in large part by southward flowing ice associated with the Keewatin ice regime. Silty till (unit 3), in contrast, is derived from Paleozoic platform rock types and has a silty matrix and a high carbonate content. The silty till was deposited by westward flowing ice originating in, or east of, Hudson Bay. Tills of intermediate texture and composition were deposited where drift was carried either southwards (in the case of tills of northern provenance) or westwards (in the case of tills of Hudson provenance) across the Paleozoic-Precambrian bedrock contacts, or where ice crossed and incorporated a former till deposit derived from the contrasting rock type. Maps of both the texture (Fig. 13) and carbonate content (Fig. 14) of the uppermost till sheet clearly show the limits of the various ice flow regimes and the effect of ice flow across bedrock contacts; however, precise limits are difficult to define where older till sheets are involved.

The tills were mapped and classified according to their texture, a characteristic that is easily discerned in the field. Distinctive landforms are also associated with each till type but morphology was not used as a primary mapping criterion because the surface form of the thickest till deposits is obscured by postglacial marine and lacustrine deposits, and by peat.

Unrecognized till units may lie within the area shown as stony marine pelite (unit 6a) and as undifferentiated marine deposits (unit 6e), where thick peat and swamp prevent the accurate determination of geological boundaries in the field and make airphoto interpretation difficult.

Till of Keewatin provenance

Bouldery till (2a)

Bouldery till (Fig. 15) is widespread in the northernmost part of the area, where it forms broad belts oriented northwest-southeast, each strip being roughly 20 km wide. This unit covers about 2000 km^2 or 7% of the map area. The till, consisting of cobbles and boulders in an olive grey gritty sandy matrix, was derived from Precambrian rock types; a close spatial relationship exists between bouldery till and broken rock. An abundance of large clasts distinguishes this till from sandy till, which is almost boulder-free on a unit-volume basis. Boulder sized clasts are abraded, slightly rounded, chunks of bedrock or rock rubble; smaller clasts and the matrix derive from rock flour or from comminuted rubble. Many pebbles are rotten and crumble in the hand. There is a substantial silt component, but very low clay content in this till, and most of the fines are stuck onto the larger clasts.

The textural character of the till is somewhat varied; average textural values for the matrix are 12% granules, 65% sand, 18% silt, and 5% clay. The range in matrix textures is plotted on a ternary diagram (Fig. 16); areal sand content is shown in Figure 13. The boulder content is also variable; in some places the till has only a moderate amount of boulders, whereas in others it is composed almost entirely of broken rock, abraded and slightly rounded from glacial comminution.

Soil pits show that the upper parts of the till have a higher boulder concentration than at depth. This characteristic is probably related to two different factors:

1. In places the upper mantle is ablation or flow till, from which the finer component has been removed by meltwater. Till of this type generally has incipient sedimentary structures.

2. All bouldery till surfaces in the map area have been washed by a high postglacial sea, leaving a dense bouldery lag or boulder beach on the surface. Where this is a dominant factor, boulders are commonly more rounded than where the material is ablation till, sedimentary structures within the till are generally absent, and fines are commonly concentrated at the bases of slopes.

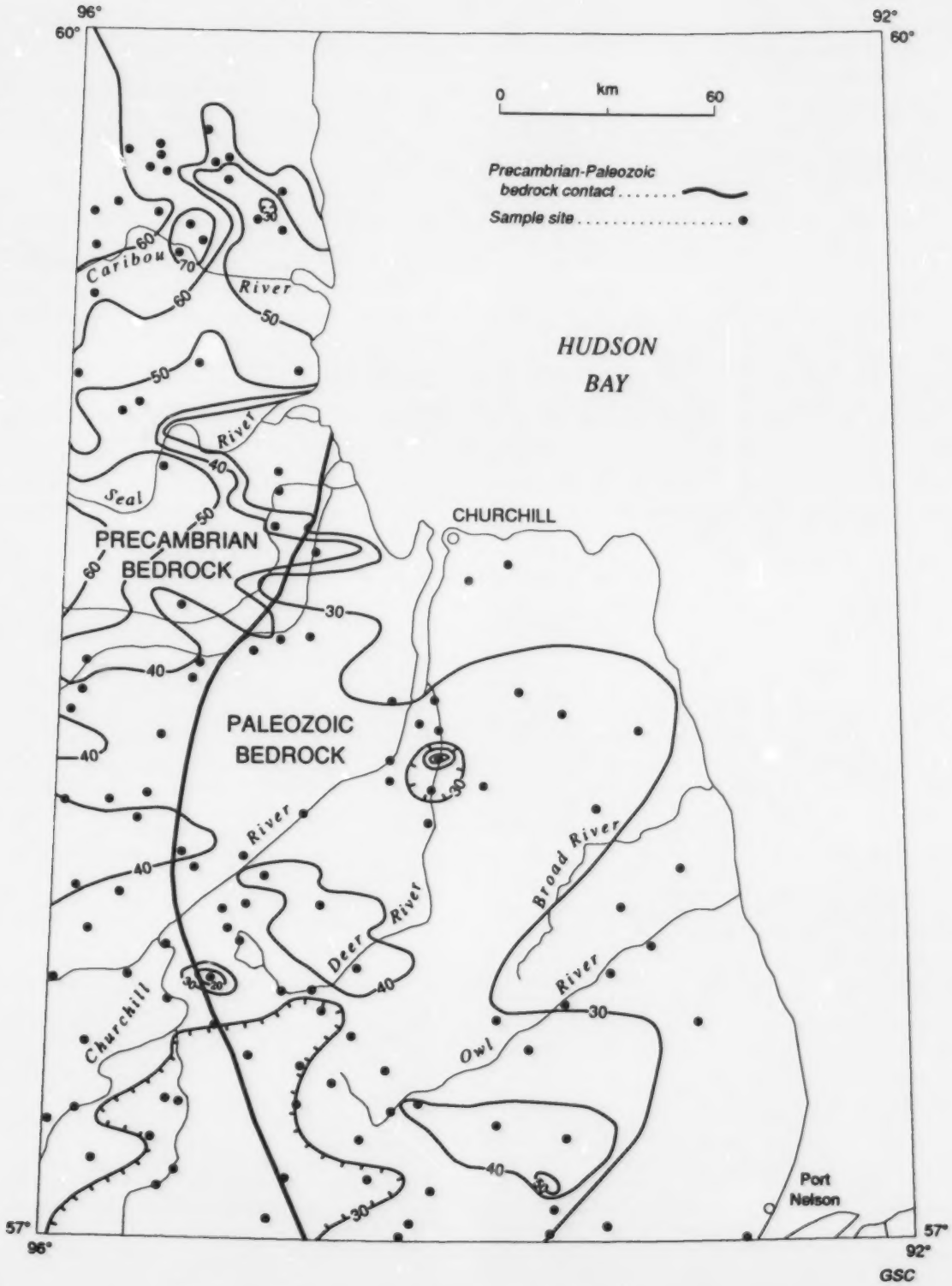


Figure 13. Sand content of the upper till sheet expressed as per cent weight on the <2 mm fraction.

Periglacial processes are active in the upper 1 m of the till and the surface is commonly strewn with mudboils. The till has a vesicular structure within these features, and most primary structures have been destroyed.

Landforms. Terrain in areas of bouldery till has a pronounced east-west fabric; elongated lakes are separated by, and defined by, ribbed (Rogen) moraine (Fig. 17). Individual ribs have an overall ENE-WSW orientation but are generally slightly sinuous. The ends of one rib commonly merge with adjacent ridges. The surfaces of many ribs are fluted perpendicular to the axis of the ridge; where flutes are prevalent, some ribs grade into drumlinoidal forms (Fig 17). The ribs vary from 2 to 5 m in height, 180 to 240 m in width, and 500 m to 1 km in length. They are asymmetric in cross-section. Northern (proximal) slopes are gentle, whereas southern (distal) slopes are relatively steep. Ribs are commonly spaced 200 to 300 m apart and shallow lakes occupy the low areas between ribs. The presence of flutes on ribs and lack of continuation of flutes from one rib to the next rib down-ice suggest that ribs and flutes formed contemporaneously. Their occurrence indicates that the ribs are subglacial bedforms rather than ice marginal recessional moraines. Their association with crevasse fillings in this region suggests that they formed during the last phases of glaciation, near an ice margin, where drift had concentrated along shear planes in a relatively thin, brittle ice cover. Indeed, this area of ribbed moraine lies near the southeastern limit of Late Wisconsinan Keewatin ice, as determined by other landforms, striae, and textural and mineralogical data.

In places, particularly where the bouldery till unit grades into rock rubble, mature rib forms are replaced by low knolls, irregularly shaped but generally elongate in an east-west direction. The "till" in these areas has little matrix and consists primarily of broken rock, mounded by the action of glaciers.

Short linear morainal segments on a smaller scale than the ribs are located near the coast between Point of the Woods and Nunalla. These ridges are oriented NE-SW to NNE-SSW. They are thought to have originated as De Geer moraines, which were subsequently intensively reworked by marine processes. The presence and orientation of these ridges indicate that in late glacial times, glacier ice in the northern part of the map area flowed into an ice-free Hudson Bay, and that the sea progressively inundated that region as the ice receded.

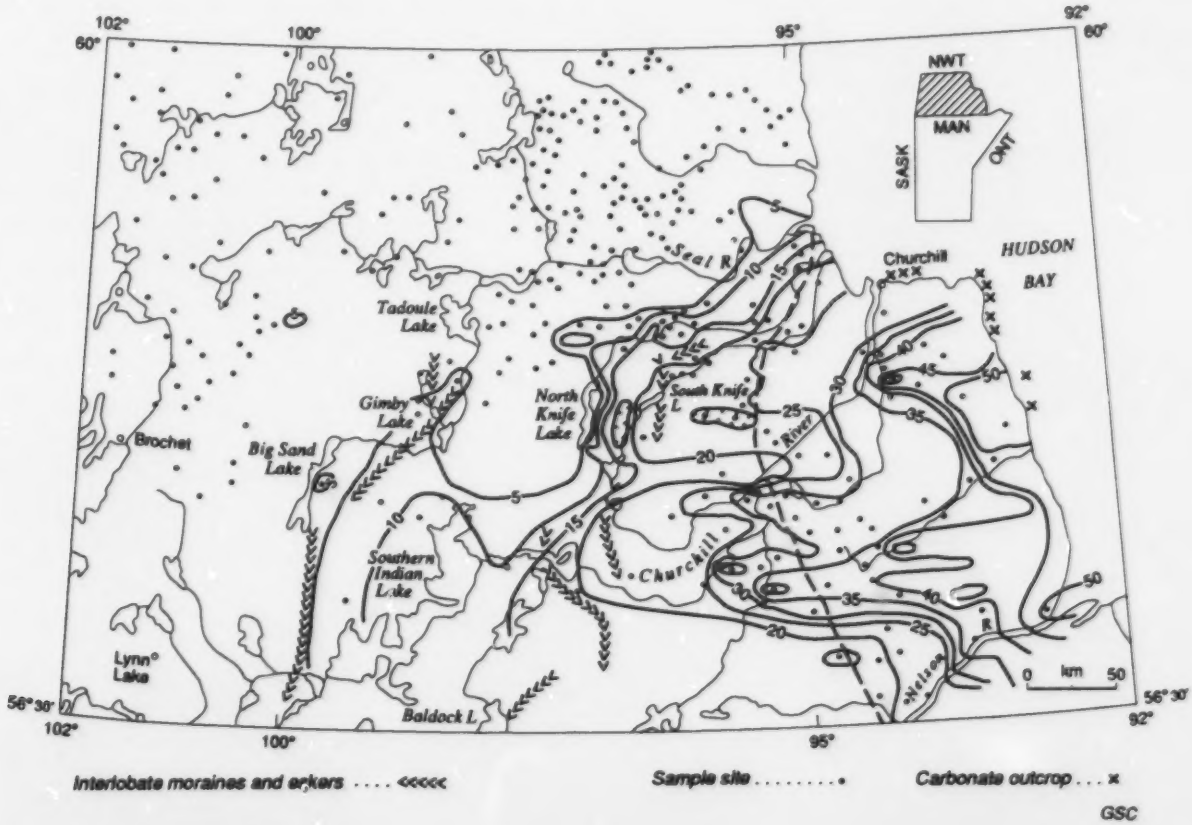


Figure 14. The carbonate dispersal train in northern Manitoba. Contours show the per cent weight carbonate of the <2 mm fraction of surface tills. Dashed line marks the boundary between Shield rocks and Paleozoic limestone (Dredge, 1988b).

A third landform associated with ice of Keewatin provenance is the remains of an end moraine east of Churchill, named the Churchill Moraine. The feature winds around and contains a number of small lakes near the coast; it can be traced over about 12 km. For most of its length it is heavily armoured by a lag of Precambrian boulders. The moraine is a recessional feature created by the same ice mass that deposited the kames at Twin Lakes and Knight's Hill south and east of Churchill (see below).

The broad, diffuse ridges farther south, in the vicinity of Mack Lake may be buried Keewatin end moraines, subsequently blanketed by silty Hudson till and glaciolacustrine deposits.

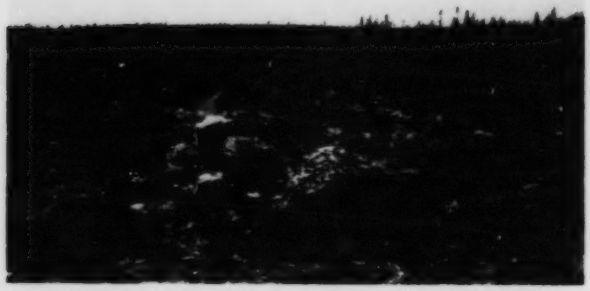


Figure 15. Surface character of the bouldery till unit. Boulders are commonly abraded blocks derived from nearby bedrock areas. (GSC 204036-H)

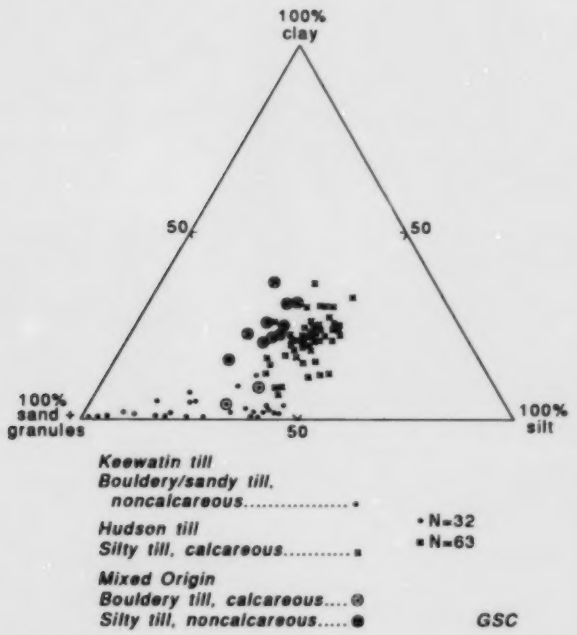


Figure 16. Ternary diagram showing grain sizes for Keewatin and Hudson tills, and tills of mixed origin.

Sandy till (2b)

Sandy till, derived primarily from medium grained granitoid and gneissic Shield rocks, is the "typical" till deposited by glaciers flowing southward from centres in central or eastern District of Keewatin. This material occurs as a surficial unit only in several small patches in the map area, one directly south of Long Lake, one near Lofthouse Lake, and two others 15 to 22 km west of the Seal River bend. These areas are characterized by gently rolling terrain and sandy surfaces having scattered boulders. Well developed mudboils form conspicuous surface features. The till matrix resembles that of bouldery till except that the percentage of granules is less and the percentage of fines is proportionately greater (typically 5% granules, 50% sand, 40% silt, and 5% clay).

Sandy till was observed in section only as far south as North Knife River, where river cuts expose a till sheet 0.7 to 3 m thick.

Till of Hudson provenance

Silty till (3)

Silty till was deposited by ice moving westwards out of or across the Paleozoic carbonate terrain of Hudson Bay. It underlies the southern two-thirds of the map area. Although this unit makes up a substantial component of the Quaternary deposits, being up to 60 m thick, it is seen only in sections along North and South Knife, Churchill, Little Churchill, Little Beaver, Owl, and Deer rivers, and the Nelson estuary. In the southwest part of the map area (i.e., west of the Great Beach), silty till is overlain by lacustrine deposits and thick, forested bog or fen peat. In many places, these cappings are thin enough that the underlying till can be reached using shallow drilling equipment and hand augers. Such units are designated as unit 3. In central and southeastern parts of the area (i.e., north and east of the Great Beach) silty till is overlain by marine deposits and either bog or ice-wedge patterned peat. Those areas commonly have till within several metres of the surface.

The silty till unit consists of one to four sheets of till. Each sheet is 2 to 6 m thick and is separated from the others by thin beds of sand and gravel or organic layers. The tills are greyish or brownish, calcareous, fine grained, and slightly to

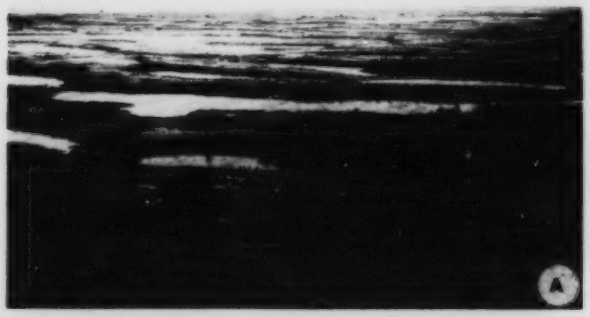


Figure 17A. Ribbed moraine landscape showing ridges of bouldery till and intervening lakes. (GSC 204036-G)

moderately plastic; they are derived primarily from Paleozoic limestone and dolomite and were deposited by glaciers flowing out of or across Hudson Bay. All tills are sparsely fossiliferous and contain shell chips 1 to 3 mm across. These fragments were incorporated into the till at one or more times when Hudson ice overran nonglacial marine deposits in Hudson Bay. The average grain size for the silty tills is 2% granules, 33% sand, 43% silt, and 22% clay. The till is relatively stone free. Figures 13 and 16 indicate the amount of areal variation in the tills.

The average carbonate content of the <2 mm fraction of the silt till, determined by acid digestion, is 34%, with values ranging between 9 and 52%. Limestone and dolomite make up between 26 and 92% of the pebble fraction. Carbonate content in the uppermost silty till sheet is shown in Figure 14. The lowest carbonate contents in both the pebble and matrix fractions lie near the northern and western limits of the till sheet. Both texture and carbonate content reflect the progressive incorporation of Shield rocks: there is a sharp drop-off of carbonates and a corresponding, but less

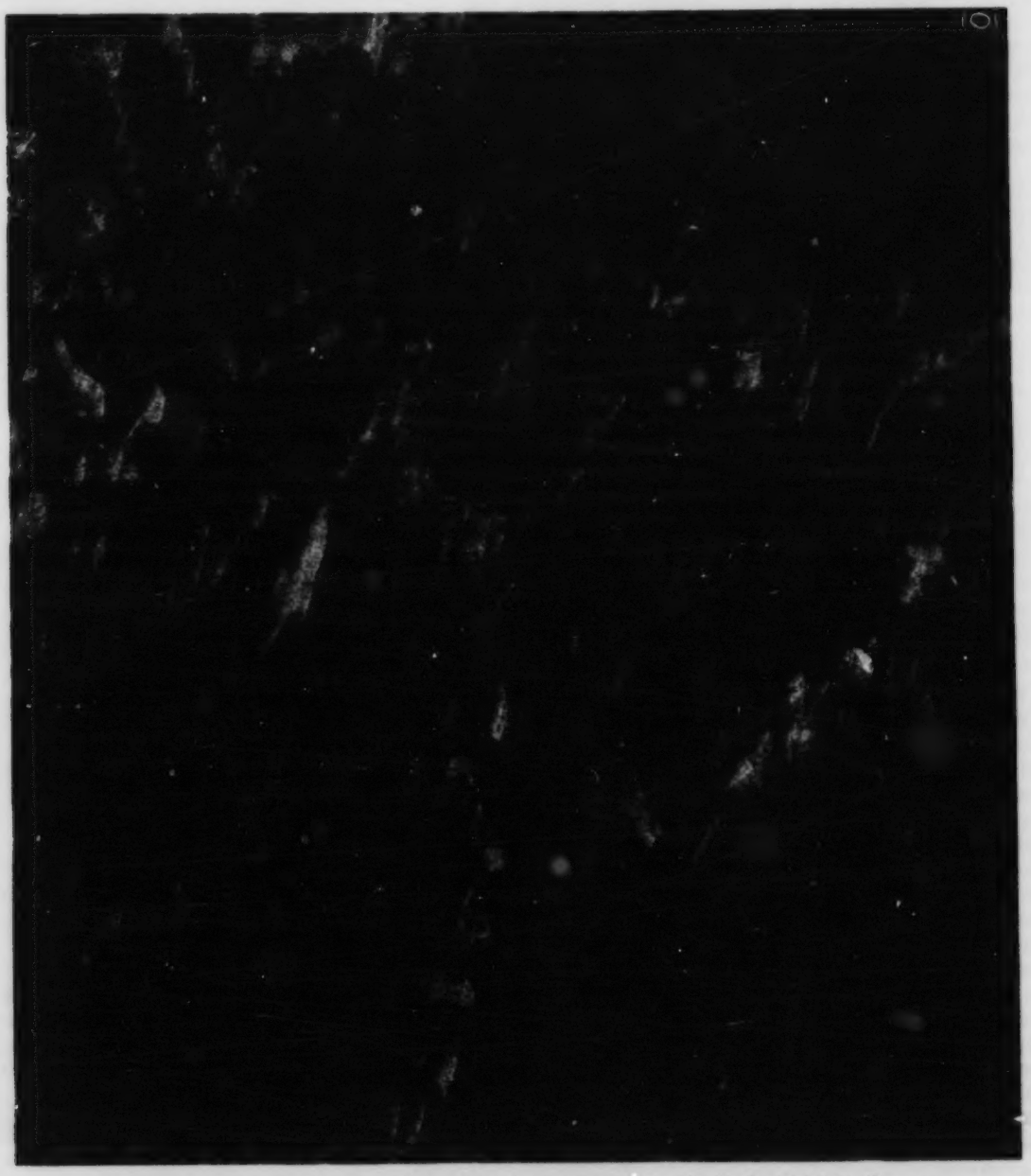


Figure 17B. Fluted ribs: gradation from transverse to longitudinal glacial bedforms. Scale 1:60 000. (NAPL A15836-101)

pronounced, coarsening of the till east to west beyond the Paleozoic-Precambrian contact. A sharp decline in carbonate content occurs between Seal and Churchill rivers, where Hudson ice overran and incorporated older sandy till of northern provenance. The mixed nature of till near this northern limit of Hudson ice is indicated on the ternary diagram (Fig. 16). Minor variations in carbonate content also result from small differences in source rock characteristics. High carbonate contents near the mouth of Broad River correspond to an area where limestone outcrop lies at or near the surface; a small carbonate plume can be traced down-ice. The larger, elongate carbonate plumes in the south cannot be explained by the proximity of outcrop; these may relate to ice streams flowing within the main Hudson ice mass (Dredge, 1988b). The calcareous till has been leached to depths of 0.6 m, for frozen till, and up to 3 m in nonpermafrost terrain (Dredge, 1988a). Some observed variations probably result from sampling leached material.

The lower till units are grey to black, contain crushed shell fragments, and show little sign of water sorting. The grey tills are compact and have a distinctive fracture. The younger of the grey tills have unoxidized, closely spaced joints; till blocks break into hackly, pebble sized fragments. The spacing of joints and degree or depth of oxidation along joint surfaces increase with depth; the lowermost and older tills cleave into larger blocks (about 20 cm wide) along heavily manganese stained, irridescent, weathered joint surfaces.

The red-brown to buff uppermost silty till differs from those below in that it is generally more plastic, contains granule sized mud peds, is only moderately compact, and is substratified in the top 1 m. This till contains a few clasts of red mudstone. These clasts, the red-brown colour, and the finer texture of the till indicate that it is partly derived from the red shale and mudstone that underlie the central part of Hudson Bay. The unit grades upwards into glaciolacustrine waterlaid till.

Landforms. Airphoto interpretation, combined with data from auger holes, indicates that the till surface forms a gently undulating plain with little local relief – a marked contrast to the ribbed moraine landforms associated with terrestrial Keewatin till. Within this ground moraine are a number of swells with broad, even crests. The largest, lying 30 km west of the Great Beach, is about 5 km wide and 10 m high and is composed of segments having a combined length of 60 km. These broad ridges are gently arcuate but have an overall north-south orientation. Their form suggests that they may be subaqueous moraines associated with halts in the recession of Hudson ice where the ice front formed a calving bay adjacent to Lake Agassiz. On the other hand, some could also pre-date last glacial events. The easternmost of these broad swells, north of Weir River (57°N, 93°35'W), protrudes through the regional cover of peat and marine deposits. This feature has been broken up and partly re-oriented into drumlinoidal forms indicative of a localized late-glacial readvance of partly grounded ice that moved towards the south-southwest.

A second set of smaller ridges, still low and broad, lies north of Churchill River in the vicinity of Mack Lake. The long axes of these ridges are oriented east-west. Till in these ridges, though silty, is sandier than the average silty till, contains less carbonate in the matrix, and has a higher percentage of Precambrian clasts (the circled sites in Fig. 16). The position and composition of these ridges suggest that they mark former recessional limits of Keewatin (northern provenance) ice.

Glaciofluvial deposits

Glaciofluvial deposits, although covering only about 2% of the map area, are significant because some contain large volumes of sand and gravel. The most extensive deposits, lying north of Seal River, were formed by the backwasting and stagnation of Keewatin ice. Crevasse fillings, kame moraines, and isolated kames, eskers, and outwash described here belong to a spectrum of deposits that reflects the effects of running water, beginning with fluvioglacial and glaciofluvial ice-contact deposits, progressing through submarginal and proglacial fluvial deposits, and ending with alluvium. The location of glaciofluvial deposits bears little relation to the modern drainage pattern and commonly cuts across the path of present day streams. Older alluvium, in contrast, is commonly located in the vicinity of modern streams and generally marks antecedents of them.

Conjugate ridges (crevasse fillings) (4a)

These features occur in the northernmost part of the map area in three belts about 2 km wide and 30 to 40 km long. The belts trend south-southeast and alternate with belts of ribbed moraine described under *Bouldery till*. On airphotos the boundaries of these belts are abrupt and blocky in shape.

The terrain is made up of sets of reticulated ridges (Fig. 18) or, in some places, hummocks. The largest ridges are about 5 m high and consist of a combination of sandy or bouldery till and poorly stratified water sorted material (e.g., 5% granules, 53% sand, 42% silt-clay). Between the larger ridges are numerous reticulated smaller ridges, composed of better sorted sand and pebble gravel and commonly exhibiting planar or cross-stratification. A typical texture for these is 6% granules, 76% sand, 18% silt, and 0% clay. These sediments are derived from bouldery till.

These features, interpreted as crevasse or fracture fillings, indicate that, in its late stages, Keewatin ice was brittle and zonally stagnant. The occurrence of large ridges, together with the inset network of smaller, closer ridges, indicates that in situ downwasting occurred. The lower ridges formed during progressive downwasting and increased fracturing of the ice as increasing amounts of running water became available. The proximity of these features to fluted ribbed moraine areas suggests that the ice sheet was not totally stagnant and that more active flow was maintained in some places.

Kame moraine (4b)

An eastern extension of the South Knife kame moraine, a major landscape element in northwestern Manitoba (Dredge et al., 1986), forms a prominent ridge about 30 m high where South Knife River crosses the western boundary of this map area. The kame is hummocky and terraced on the south. Below 145 m the surface has been reworked into beaches. The surface of the kame moraine is sandy and essentially free of boulders; the steep slopes suggest that the core may be composed of larger or more cohesive material. The sandy material is current-bedded, with the direction of dip to the southwest. This ridge likely formed at the junction of the Late Wisconsinan Keewatin and Hudson ice masses.

Two sets of widely spaced interlobate-kame segments can be traced northeastwards from this main ridge to the Holcroft Lake area and Button Bay. These features have been strongly modified by littoral processes and the surface has been flattened and reworked into beaches.

Kames (4b)

Hummocky kames and isolated knolls are scattered throughout the northern half of the area. Those in the vicinity of Long Lake create rough terrain with 5 to 8 m relief.

Thin, stringy kame deposits cap the west sides of the till mounds near Cooper Creek (the south central limit of the map sheet). These features lie adjacent to meltwater channels and are related to ice marginal drainageways.

Two large kames east of Churchill provide an interruption in the otherwise featureless landscape. The small kame, forming Knight's Hill east of Norton Lake, has a bouldery north slope about 10 m high; 95% of the boulders are Precambrian. Materials grade to sands on the south side; the northerly and easterly slopes are steep and are interpreted as ice contact faces. The Twin Lakes kame is a triangular and wedge-shaped deposit about 8 m high, 5 km long, and 3 km broad at its widest (north) side. Again, the northern part of the kame consists of poorly sorted sand and gravel of mixed lithology; the southern part consists of better sorted, better stratified sand and finer gravel. The upper surface and north slope are kettled; the south side and flanks are beached. Remnant Keewatin ice may have lain along the north side and part of the top of the feature while the remaining part of the kame was being reworked by the sea.

Eskers (4b)

Eskers comprise the most voluminous localized sand deposits in the area. These features were formed within both the Keewatin and Hudson ice masses, although their environment of deposition, texture, and lithic composition differ from one ice regime to the other.

In areas affected by Keewatin ice, the eskers are small to medium sized and of variable length. Most developed during late phases of deglaciation and are associated with other decaying ice features. Six major eskers and many short segments lie in the area of Keewatin ice as far east as Cape Churchill. Most are oriented north-south, but a few small segments near Nunalla trend south-eastwards towards Hudson Bay and are thought to have formed just prior to deglaciation, when part of the Keewatin ice margin lay near the coast of Hudson Bay. The largest esker, south and west of Seal River, is a steep sided feature about 50 km long and up to 25 m high. Above 165 m elevation the surface is pitted. Below this level are numerous beach ridges have formed on the eastern side. Most other eskers lie well below the limit of marine submergence and have been altered by marine processes. As a result they are broadened, commonly reduced to less than 5 m in height, and reshaped into beach ridges. Some of the north-south trending ridges about 50 km southeast of Churchill mapped as raised beaches, may have originated as eskers. The Keewatin eskers are composed primarily of sand although patches are boulder armoured; some segments are composed of sand and gravel. West of Churchill the sands and gravels are of Precambrian lithology; east of Churchill as much as 70% of the gravel fraction is derived from carbonate bedrock.

Eskers associated with Hudson ice are longer and larger and developed when Hudson ice was still actively flowing. Two large eskers, with kettled surfaces and irregularly spaced nodes, are associated with Hudson ice. They originate at the height of land (240 m) south of Bradshaw Lake and trend southwest as two parallel ridges 25 km apart. The eskers are about 20 m high and stand well above the surrounding swamp. Parts of these esker systems lie beside and within the Churchill and Little Churchill River valleys; they emerge from the valleys where the valleys deviate from the southwest-northeast trend. The eskers were formed by meltwater flowing southwest, probably emptying into Lake Agassiz. One esker delta lies at 240 m, where the esker crosses Churchill River at Mountain Rapids. The eskers consist primarily of loose calcareous silty sand or fine sand, massive to poorly stratified, with lenses of small pebbles of mixed granitic and limestone rocks.

Outwash (4c)

Outwash deposits are of limited extent in this region. Because meltwater channels are all now occupied by fens, we have no ground data on texture and composition of the outwash deposits; presumably they consist of sand or sandy gravel. Three partly connected, broad, flat-floored ice marginal or subglacial channels lie in the southernmost part of the map area. These north-south oriented channels trend across the slope of land. Additional outwash-like deposits are associated with channels aligned with, or flanking, southwest-trending esker systems, and relate to subglacial drainage towards the Hudson ice front. Similar deposits are also associated with eskers formed within Keewatin ice but are too small to depict on the map.

Figure 18A. Belt of gravelly conjugate ridges (crevasse fillings) surrounded by ribbed moraine. (NAPL A14676-136)

Glaciolacustrine deposits and landforms (5a, 5b)

Description and distribution

A major glacial lake, bounded on the north and east by Keewatin and Hudson ice, occupied the area vacated by the receding ice toward the close of glaciation. Sediments deposited into this glacial lake form the surficial inorganic (5a and 5b) unit in the southwest quadrant of the map area. They are found at the surface from an elevation of 130 m (the Great Beach) to 245 m (the height of land). They cover an area of 13 000 km^2, roughly 25% of the map area. Below 130 m elevation, glaciolacustrine deposits underlie marine deposits but are seen only in riverbank exposures. The northern limit of buried deposits lies slightly north of North Knife River (58°40′N). The eastern limit is less certain: glaciolacustrine deposits were observed as far east as Teepee Falls (95°10′W) on North Knife River, at least as far east as Limestone Rapids on Nelson River, and possibly as far east as Port Nelson. (The assignment of "lacustrine" to the sediment there is less certain.) Lacustrine deposits were not observed along Churchill River east of the Great Beach. In other places river cuts were not deep enough to indicate whether glaciolacustrine deposits were present.

Glaciolacustrine deposits, varying in thickness from 1 to about 6 m, mantle the till and drape over southwest-trending eskers. Where deposits are less than 2 m thick, accompanying Map 1617A shows the underlying till.

Where glaciolacustrine deposits are the surface inorganic unit the airphoto pattern is one of raised arabesques. This pattern, created by innumerable raised bogs and low fens, together with thermokarst depressions, forms a ubiquitous and continuous organic cover on the glaciolacustrine deposits. The general airphoto surface aspect is thus unrelated to substrate morphology.

General nature of deposits

Areal information on glaciolacustrine deposits comes from shallow cores that penetrated the surface stratum of frozen peat. In some places, sedimentary structures were well preserved in the frozen core; elsewhere, the material was disturbed, and only general observations about the material could be made.

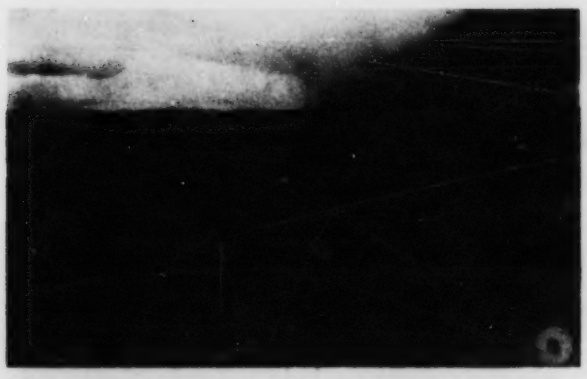


Figure 18B. Ground view of ridges showing their orthogonal geometry. (GSC 190626)

Most glaciolacustrine deposits consist of stiff calcareous clayey silt, with granules of rock and clay. Lacustrine sands are scarce. An average texture for the glaciolacustrine deposits is 19% sand, 63% silt, 18% clay, but a substantial range in texture occurs from site to site (sand 0 to 33%; clay 4 to 33%). Within a given 3 m core, there is commonly either no change in texture throughout the core or else a slight fining upwards trend.

Massive glaciolacustrine deposits in northeastern Manitoba are grey to red-brown, depending on whether they derive from Keewatin till or the upper brown silty till of Hudson provenance. Within the map area they derive primarily from the brown till and are characteristically chocolate brown to brick red and stronger in hue than their parent till. The enhanced colour probably is caused by 1) the relatively high concentration of iron minerals in the fine fraction from the till, which is the main constituent of the glaciolacustrine deposits; and 2) increased oxidation of iron colloids as fine particles drifted through the water column in the glacial lake. In laminated deposits where texture varies from layer to layer, as in the case of varves, colour banding is characteristic.

The silts are calcareous and the average carbonate content is 25% (range 13 to 30%) in this area. Carbonate is present in lacustrine deposits that overlie non-calcareous tills of northern provenance as well as calcareous tills of eastern provenance. Carbonate contents of 5 to 11% have been measured near the Saskatchewan border, in the far western reaches of the lake basin, far beyond the limit of carbonate till (Dredge et al., 1986). This content indicates that the glaciolacustrine sediment has been transported long distances in suspension.

The glaciolacustrine clayey silts are moderately plastic; the average liquid limit is 24 and plastic limit is 16. Water contents lie between the liquid and plastic limits. Where soils are particularly fine grained, capillary tension keeps water in its liquid state despite subzero soil temperatures (as low as -4°C in summer). Slightly coarser soils have a moderate bonded-ice content and low amounts of segregated ice. In both clayey and silty soils, a layer of segregated ice commonly lies between the glaciolacustrine sediment and the overlying frozen peat.

Soil drainage is poor because the sediments are fine grained and ice occupies interstitial voids. This condition has contributed to the development of the overlying peatland.

Sedimentary facies

On the basis of observations from frozen cores and small riverbank exposures, the silty glaciolacustrine deposits can be subdivided into several units, each of which has specific characteristics reflecting a different environment of deposition (Fig. 19). The environment of deposition varies from glacial submarginal (waterlaid till) and near marginal

(current deposits and varves) to distal (massive silt and clay). At sites where more than one unit is present the sequence is massive clay, overlying varves, overlying till; this order suggests a continuously receding ice mass. Sand was found at the top of a few cores from the area between Mack Lake and Churchill River.

Waterlaid till

This calcareous deposit grades downwards into the upper brown silty till described previously. The waterlaid till is diamictic in some places, but grades laterally into poorly stratified or discontinuously stratified beds over short distances. Pebble layers and graded beds were observed in some sections. The average texture is 3% granules, 28% sand, 48% silt, and 21% clay, similar to other silty tills. The till contains small amounts of pebbles, some of which are striated. On average, about 55% of the clasts are derived from Paleozoic sources, and about 30% of the matrix is carbonate. The till is slightly compact, has a horizontal fissility, and crumbles easily into pea-sized fragments. Because of its sedimentary structures, relatively low degree of compaction, and stratigraphic position, the unit is interpreted as a waterlaid till deposited beneath or near the floating edge of the Hudson ice mass. Slugs of flow till were produced where slurries of sediment sloughed off the surface of the ice into the lake.

Turbidite sands, varves, and rhythmites

Varved clays with a basal sand unit, are best exposed along North and South Knife rivers. The basal part of the North Knife River sequence is sand, with crossbeds and ripple drift structures indicating current flow towards the west. These currents were generated by turbid meltwater issuing subaqueously into the lake from the base of the Hudson glacier. The equivalent unit on the Nelson estuary is a massive, pebbly sand. The sands are conformably overlain by a fining upwards sequence of varves consisting of alternating grey and brick-red beds. In some couplets the red layer is significantly finer than the grey layer; in others, the two are texturally similar. The lowermost couplets are 4 to 6 cm thick; they become thinner upwards to a thickness of about 1 cm. About 150 couplets remain intact in the most exposed section; but the sequence has been truncated, and the uppermost beds have been contorted by a glacial readvance.

Rhythmites were also observed at Port Nelson and along cuts in the Great Beach at Lost Moose Creek. The beds are multicoloured – pastel grey, yellow, red, and brown – and have a silty or silty sand texture. These sequences contain only 15 to 30 couplets.

The thinning and fining upwards sequence of varves along North and South Knife rivers suggests a continuously retreating ice mass that deposited sediment into the lake for

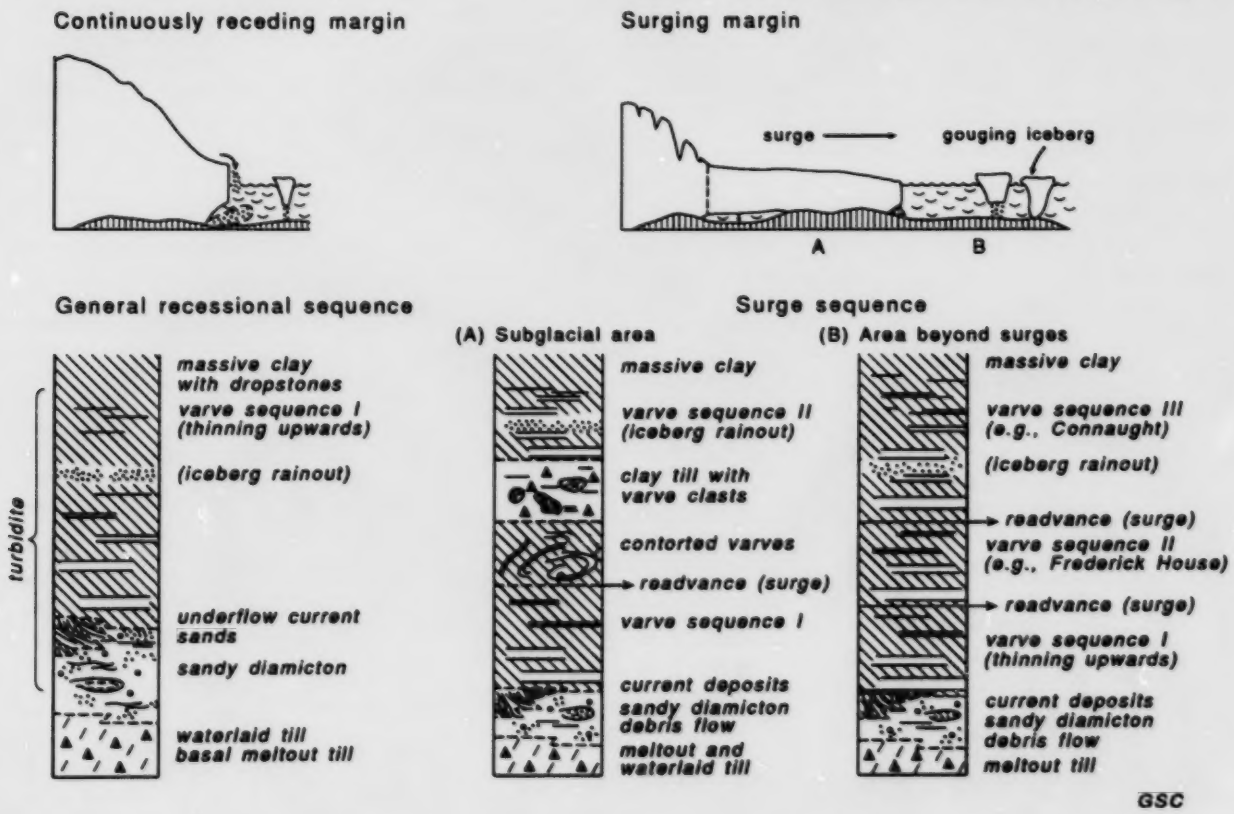


Figure 19. Sedimentary facies associated with glaciolacustrine deposition in the Hudson Bay lowlands.

at least 150 years, assuming an annual cycle of deposition. Those along the Nelson estuary farther east represent a shorter time span and, because they differ texturally and chromatically from varves on North and South Knife rivers, may belong to a different sedimentation regime.

Massive silt-clay

Massive grey-brown to red-brown clay-silt and gritty silt-clay forms a third unit, which is thought to have been deposited into the lake as suspended sediment beyond the direct influence of glacial ice as the distal part of the turbidite sequence. Deposits of this type are well exposed along North and South Knife and Deer rivers, and at Mountain Rapids along Churchill River. The massive unit is generally unbedded and contains few dropstones. There are, however, numerous granule-sized clasts of clay. These deposits vary in texture from about 40 to 90% clay. The unit is sparsely fossiliferous and contains both diatoms and small gastropods.

Surface sand

In a few auger holes, particularly those between Mack Lake and Little Beaver River, the uppermost lacustrine unit is sand (unit 5b). This sand could be either a regressional littoral deposit or simply bottom deposits derived from nearby areas of sandy glacial drift. We favour the latter explanation because, firstly, the lacustrine sands lie within areas where the till has a sandy-silty texture; and secondly, no major beaches are associated with the sand unit, or indeed with this glacial lake below an elevation of 300 m, well above the highest land in the map area.

Landforms

Glaciolacustrine sediments form a blanket mantling the underlying till plain, smoothing and subduing the topography. Ornamenting this subdued topography are patches of criss-crossing linear and arcuate grooves about 1 m deep (Fig. 20). These grooves are most commonly found on crests of till ridges that lie between 210 and 240 m a.s.l. Interpreted as iceberg furrows or scour marks, these features formed where the keels of icebergs, calved from the Hudson and, to some extent, the Keewatin ice masses, were dragged across topographic rises on the lake floor. Craters within furrows indicate places where ice blocks have melted.

There are no lacustrine beaches in the field area, but notches cut into till ridges at 185, 210, and 245 m in the vicinity of Fly, Owl, and Turcott lakes may mark regressional lake levels.

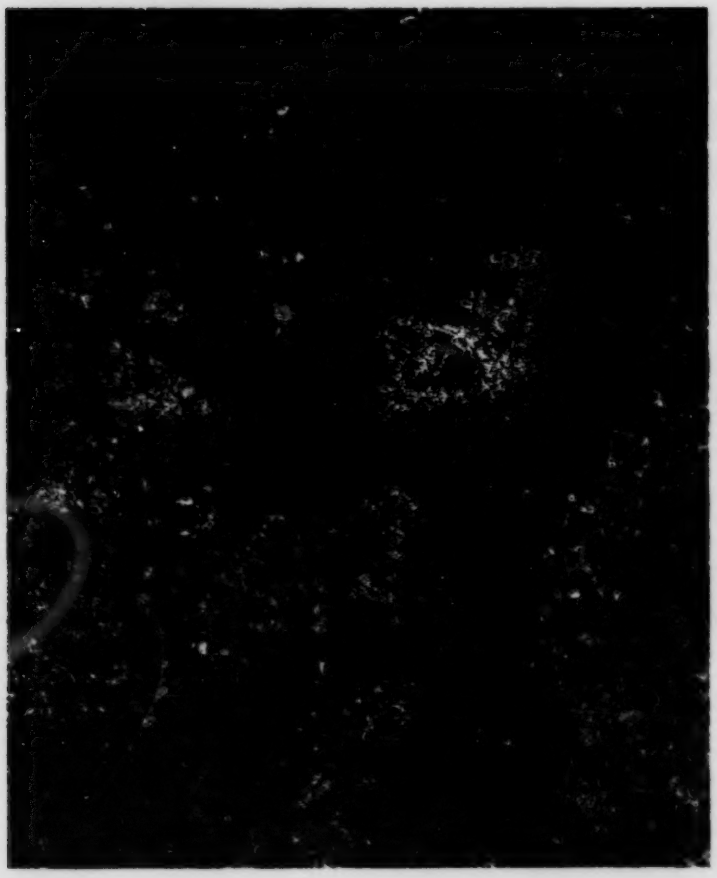


Figure 20

Iceberg scour marks: linear grooves, arcs and pits generated by iceberg keels scraping across and grounding on underwater ridges on the floor of Lake Agassiz. (NAPL A-14128-21)

Table 1. Characteristics used to differentiate nonfossiliferous marine and lacustrine deposits

Parameter	Marine deposits	Lacustrine deposits
Colour	Grey	Brown
Sequence of deposits	Coarsening upwards	Fining upwards, or no change
Landforms	Beaches	Wave-cut notches, iceberg scours, no beaches
Stratigraphic position	Uppermost	Below marine, and in places below till resulting from surges

Glaciomarine and marine deposits

Distribution

More than two-thirds of the map area was inundated by a postglacial sea. As this sea receded to its present level it reworked, transported, and redeposited the underlying glacial sediment. Marine sediments overlie till and, in places, glaciolacustrine deposits from which they were derived. They in turn are mantled by organic units but are exposed around tundra (thermokarst) ponds and in river bank sections. South of Seal River marine sediments form an extensive seaward thickening wedge between the uppermost limit of postglacial marine submergence and present sea level. Near marine limit, marine deposits are thin, and consist of till and lacustrine sediment only slightly redistributed by marine processes. The exact limit of marine influence is thus difficult to determine. In the southern half of the map area, marine deposits extend inland from the present coast to just above the Great Beach. Almost all the terrain in the northern half of the region was inundated at some time, but most marine deposits lie between, or east of, belts of ribbed moraine below 90 m elevation. The surfaces of the moraines have been washed by the sea but sediments show little reworking and redistribution.

In northeastern Manitoba, marine sediments have been differentiated from lacustrine sediments on the basis of colour, sequence of deposits, suite of landforms, and stratigraphic position (Table 1); in places there are also diagnostic fossils. In a number of instances, differentiation was difficult, however, particularly where blanket sands lie beneath peat just above the Great Beach and in sections having rhythmically bedded sandy silts. Consequently, the map shows a dashed line between marine and lacustrine deposits.

Offlap sequence: undifferentiated marine deposits (6e)

Marine deposits in this region, with one exception, form a coarsening upwards offlap sequence, indicating a continuously regressive sea. The sedimentary sequence forms a seawards thickening wedge, varying from about 1 m in thickness near the upper limit of postglacial marine submergence, to about 8 m near the present coast. The lowermost unit, a compact, glaciomarine deposit of stony silt, contains crushed shell fragments. This unit is overlain by massive silt, which grades upwards into stratified silt and silty sand. These silts in turn are capped by littoral sands or gravelly beach ridge complexes, or intertidal silts, or both. Peat deposits mantle the sequence.

Where all facies occur in sequence in equal proportion, or where different facies could not be differentiated because of the peat cover and lack of field data, the grouped unit (6e) was used. In other places the map shows the dominant facies. Surface deposits of silty offshore pelite were too small to be depicted at 1:500 000 but do appear on the corresponding 1:250 000 scale maps.

Stony marine and glaciomarine deposits: stony pelite (6a)

Stony marine deposits from 1 to 4 m thick occupy low areas between belts of ribbed moraine in the region north of Seal River (NTS 54M); commonly they blanket older deposits below an elevation of about 60 m in areas to the south. The material is grey, diamictic or poorly sorted stony to gritty silt. Textures vary greatly across the region but the average matrix is 4 to 12% granules, 30 to 50% sand, 25 to 50% silt, and 8 to 16% clay. Sediments north of Churchill (i.e., derived from sandy till or granitic rocks) are somewhat coarser than those south of Churchill (derived from silty till and limestone). Similarly, carbonate contents of the matrix vary from 14 to 50%, depending on the parent material. The pebbles are of mixed lithology, but even in areas of calcareous substrate about 50% of the clasts are granitic. The sediment is nonfossiliferous or contains shell fragments of various sizes and thicknesses. The material is nonplastic and contains ice blebs, ice crystals, stratified ice, and lenses of massive ice. Where these deposits lie within 1 m of the surface they form a blanket of low relief (1 m/km), with numerous mudboils 1 to 2 m in diameter.

The origin of this material is unclear, in part because the sediment was generally observed disturbed, in shallow soil pits and auger cores. North of Seal River, where the marine unit is commonly only 1 to 2 m thick and the prevalence of mudboils indicates active frost churning, the stony deposits are considered to be a mixture of marine pelite and till. Farther south, exposures near the mouth of Deer River show that the stony pelite is till-like in fissility, in its inclusion of old, worn shell fragments, and in its general lack of bedding structures. These deposits could be of glaciomarine origin, but they might also be deepwater marine deposits with pebbly gritty inclusions dropped from sea ice. Sediment now being deposited in Hudson Bay, which is frozen for much of the year, has a similar diamictic texture.

Silty marine pelite

The marine pelite represents the offshore and nearshore facies of the sedimentary sequence. This unit is not generally exposed at the surface but underlies the blanket sands (described later) and comprises part of the undifferentiated unit 6e. Deposits form a wedge of 2 to 8 m thickening seaward. The main exposures lie in the eastern half of the area along Owl, Deer, and Churchill rivers, and farther inland along North and South Knife rivers and Little Seal Lake. The sediments consist of grey, massive, deepwater or offshore clayey silt, occasionally plane-bedded and grading upwards into nearshore deposits of grey stratified silty sand 1 to 3 m thick. They are capped by littoral sand. Texture of the typical massive deposits is 12% sand, 74% silt, and 14% clay. Carbonate contents range from 15 to 50% for deposits south of 59°N, which are derived mainly from calcareous silt till, and 0 to 10% for those few scattered thin deposits north of 59°, derived in part from the fine fraction of granitic sandy till. Marine pelite encountered in cores included large amounts of stratified ice and many blebs of white ice. The silts are fossiliferous.

Intertidal silts (6b)

Tidal flats occupy an extensive platform extending 5 km beyond the present coast. The principal deposits on this platform are intertidal silts and numerous ice rafted granitic and limestone boulders. Relict tidal flats extend inland for about 20 km, to an elevation of about 15 m. Much of the sediment constituting these flats is grey, nonplastic laminated silt (about 44%) and very fine sand (38%), with steel grey organic blebs. Deposits lying seawards of the present coast are unfrozen in summer. Above the modern tidal zone, ice contents remain high.

Like their modern counterparts, the relict deposits form a featureless plain littered with ice rafted boulders. The silts are capped by stringed fen or thin, blanket fen deposits.

Blanket sands (6c, 6e)

Littoral and sublittoral blanket sands constitute the uppermost stratigraphic unit of the regressional sequence of Tyrrell Sea sediments. They cover one-third of the map area as units 6c and the upper part of 6e. The sandy deposits are found up to 180 m northwest of Seal River but only up to 140 m in areas farther south.

Most of this unit is overlain by a blanket of frozen peat 2 to 4 m thick, but deposits are exposed around the edges of permafrost lakes.

Blanket sands have been mapped as a separate unit near the marine limit where other members of the offlap sequence are relatively minor, and at lower elevations between beach ridge sets. The sediments are 1 to 3 m thick; they are thinnest at higher elevations, where the marine effect was limited to reworking the upper part of till and glaciofluvial deposits, and where unmapped patches of till may lie below the marine unit. The deposits consist primarily of sorted, stratified sand with some gravel, but rounded cobble gravel and limestone flags cover a wide swath between Churchill and Cape Churchill. Littoral deposits are fossiliferous below an elevation of about 60 m; shells were found at only one locality above this level.

Blanket sands are part of the sediments forming the extensive, almost flat, featureless marine plain that rises inland at a rate of about 1 to 2 m/km.

Sand and gravel beach ridge complexes (6d)

The degree of development of beach ridges relates to local topography, and to the rate of emergence of the land. Numerous small sand and gravel beaches have developed where glaciofluvial features and sandy ribbed moraine provide topographic relief. Beaches are widely spaced and poorly developed in areas of subdued terrain above 60 m a.s.l., although bouldery lags can be found on rises. Below 60 m beaches are again better developed and more closely spaced because the land has emerged relatively slowly over the past several thousand years. Beach ridges that formed from eskers and kames associated with Keewatin drift (e.g., the ridges between Lovett Lake and Knight's Hill) have a high percentage of granitic pebbles. Ridges derived from Hudson drift are calcareous or have mixed compositions.

Small isolated beach ridges, 1 to 3 m high, are prevalent north of 59° as the reworked remnants of small glaciofluvial features.

Three sets of major constructional beach ridges form prominent landscape features. The northernmost flight of raised beaches developed on an old frontal moraine of bouldery till, in the southwest corner of NTS 54M (59°10'N; 96°W). The flight rises from an elevation of 150 to 175 m.

The largest continuous feature is the Great Beach, which crosses the southwest quadrant of the map area in a 200 km long arc between Cooper Creek in the south and South Knife River in the west. It rises from an elevation of 130 m in the south to 140 m at its northwestern limit. This feature is composed of a set of beach ridges 500 m wide, having multiple hooks and spits (Fig. 8) and ridges 2 to 6 m high. This beach may be a secondary feature, developed on a pre-existing kame or moraine, the origin of which is uncertain; at the borrow pits at Silcox and in several river cuts, marine gravels account for only the upper 2 m of sediment. The rest of the ridge is composed of kamey gravel and clay till.

The most abundant beach ridges lie near the present coast between Cape Churchill and Port Nelson where they are concentrated at 60, 40, 25 to 30, and below 13 m a.s.l.

Alluvium

Older alluvium (7a)

Stream deposits and river channels unrelated to the present river regime are much more areally abundant and voluminous than modern alluvium. They occupy significant areas along Churchill, North and South Knife, and Owl rivers, and Kelsey Creek, where they lie adjacent to the modern streams but at

the level of the surrounding plain. The modern streams are incised through them. The most prominent features are the anastomosing channel remnants at Running Landing Rapids (Churchill River), 30 m above present river level, and at Long Island. Similar channels, some with oxbow lakes, flank the northward flowing reaches of North and South Knife rivers. In the case of Churchill and South Knife rivers these channels are incised into till and may be a distal facies of outwash, but the channels along North Knife, Owl, and Lower Churchill rivers, and Kelsey Creek were cut into marine silts and clays and therefore post-date the marine episode.

The deposits associated with the channels consist of 2 to 4 m of cross-stratified sand and rounded gravels, which grade in some places into estuarine sands. Sorting and sedimentary structures vary from site to site, and vertically from bed to bed. The gravel fraction north of, and including, Churchill River has a major granitic component. Gravel fractions to the south are primarily composed of carbonate.

Modern alluvium (7b)

Minor quantities of modern alluvium cover areas large enough to depict on the maps. It occurs as point and channel bars along the Churchill, upper Owl, and Deer River valleys; as bottom sediments along the lower Owl River, and Kelsey and Goose creeks; and as delta islands at the mouth of Knife and Seal rivers. These deposits consist of thin veneers of well sorted stratified sand and gravel.

Peat

Peat forms a nearly continuous blanket over the Hudson Bay lowlands and the adjacent interior south of the treeline, and masks all other Quaternary deposits in those areas. It is by far the most extensive surface material within the map area and forms part of the largest tract of organic terrain in North America. Peatlands are shown as a swamp symbol on Map 1617A, and as differentiated peat types on the inset. Peat was mapped according to its surface morphology (i.e., its airphoto aspect) but in many cases the classification also differentiates types of peat.

Five morpho-compositional peat types were recognized: forested bog peat with thermokarst ponds, open tundra peat with ice wedge polygons, wet fen peat, coalesced peat blisters, and a fen meadow peat and mineral soil complex.

Forested bog peat with thermokarst ponds

This terrain unit is composed of spongy, forest covered raised bogs (Fig. 21) and narrow fens, interspersed with thermokarst depressions (Fig. 9) that give the terrain a pitted appearance on airphotos. This peat type prevails in the interior part of the region southwest of an imaginary line running between Port Nelson and North Knife River, where it intersects the western edge of the map area. The peat is commonly 2 to 4 m thick and overlies virtually all lacustrine deposits, and some marine sediments. It is yellow to brown and consists of a stratified mixture of amorphous to fibrous moss peat and woody peat, containing some layers of charcoal. Deposits are derived from the accumulation and partial preservation of a spruce forest cover with a lichen-moss-shrub understory. The oldest date on basal peat in northeastern Manitoba is 6280 ± 80 BP (GSC-2760) from Charlebois. A log at the base of a sphagnum bog along Churchill River gave a date of 5960 ± 100 BP (BGS-980; E. Nielsen, personal communication, 1985).

The peat is moist to wet above the frost table. Permafrost is present throughout this unit below a depth of 15 to 35 cm. Random ice crystals and thin ice strata make up 30 to 50% of the volume of the more hummocky bog areas. These ice bodies do not develop at present in areas of forest cover, but palsa are currently developing in adjacent thermokarst depressions and fens.

The regional terrain is almost flat. Microrelief, in the form of ovoid thermokarst pits 30 to 100 m across, is about 2 to 3 m. These pits rarely extend below the peat into the mineral soil.

Tundra peat with ice-wedge polygons

This unit forms a tract about 50 km wide that lies beyond the tree line, and eastwards (coastwards) of the forested bog unit. The peat is 2 to 3 m thick and consists of mossy, fibrous peat containing ice wedge polygons large enough to be visible on

Figure 21A and B. Thick sphagnum and woody peat deposits support the modern spruce forest. (GSC 204035-S and GSC 204035-I)

medium scale airphotos (Fig. 22). Upper parts of the peat derive from a lichen-moss-heath type of tundra vegetation, but a basal woody layer, commonly encountered in cores, suggests that lower parts may have developed from a more arboreal vegetation community. Bulk and dry densities for peat in this area are 0.23 and 0.04 g/cc, respectively. The moisture content of the peat varies spatially and seasonally. The surface is sometimes dry and the active layer is usually partially drained. The peat is frozen below a depth of about 70 cm. Moisture contents of the frozen portion are commonly 600% of the dry weight, or 22% of the volume and are relatively uniform with depth. Stratified and random ground ice is present within the peat and an ice layer several centimetres thick is commonly present at the peat-mineral soil boundary. Massive ice lies below ice wedge troughs. The seasonal thermal regime of this peat type and the thermal effect of change in moisture contents have been described in detail separately (Dredge, 1979; Dredge and Nixon, 1979).

This peat type results in almost flat plains. The typical polygonal networks of ice wedge troughs (Fig. 22) measure about 15 m on a side and are depressed about 60 cm below the flat bog surface. Quasicircular thermokarst ponds, generally less than 1 m deep, occupy more than 30 to 50% of the surface area. The size and location of these lakes varies from one year to another; their growth and evolution, described previously (Dredge and Nixon, 1979), are particularly sensitive to both the thermal and moisture regimes of the peat.

Wet fen peat

Fens occur in two situations: they occur commonly along modern drainageways, abandoned channels, and other topographic depressions, including thermokarst pits within forested bog; they are also areally significant as stringed fens, 1.5 to 2 m thick, that occupy the lowlands on either side of the mouth of Churchill River, and the marine plain near Port Nelson. Linear fens along drainageways consist of wet, dense, amorphous sedge peat, with some moss peat, which accumulated in environments with slow-flowing water. The stringed blanket fen may have developed from areas with degrading ice wedge polygons and may have a basal peat unit made of tundra vegetation types.

Fens are extremely poorly drained, and slow-flowing water is present at the surface. Permafrost is absent in fens occupying drainageways and is probably much less beneath fen peat than beneath the bog peat, because the higher thermal conductivity of wet peat enhances heat flow into the ground during summer months. Some auger cores from blanket fens contain random ice and ice coatings. Small palsa are common features in stringed fen (Fig. 23).

Fen surfaces are flat and, along drainageways, are linear in outline. Where they cover broader areas, fens typically consist of shallow pools termed "flarks" separated by low, narrow, sedge covered peat ridges termed "strings".

Coalesced peat blisters

This unit is differentiated by its morphology. It consists of alignments of coalesced peat blisters that flank small streams running through fens (Fig. 24). Each blister is about 200 m wide, and stands 1.5 to 3 m above the surrounding fenland; the mounds have depressed centres and raised rims. These features are common near the coast around Port Nelson, and south of Warkworth Lake (about 20 km south of Churchill). The main material is brown, fibrous, stratified, mossy bog peat, with minor woody peat and ice. Central portions of mounds support an open lichen-moss vegetation. Rims are vegetated with spruce and larch.

The rims are dry, but central areas, which lie near the water table of the adjacent fenlands, are wet above the frost table. The mounds have high ice contents. Shallow borings indicate that more than 50% of the volume is crystalline ice. Massive ice is expected at greater depths. They develop in two ways: firstly, by the preferential build up of mossy peat along better drained areas in fenland; and secondly by the coalescence of palsa, and subsequent partial collapse of central parts of the mounds.

Peat and mineral soil complexes: wet fen meadows with mudboils

The hybrid unit consists of a veneer of wet sedge and grass peat, through which mudboils have erupted. This complex was encountered in areas north of the treeline where

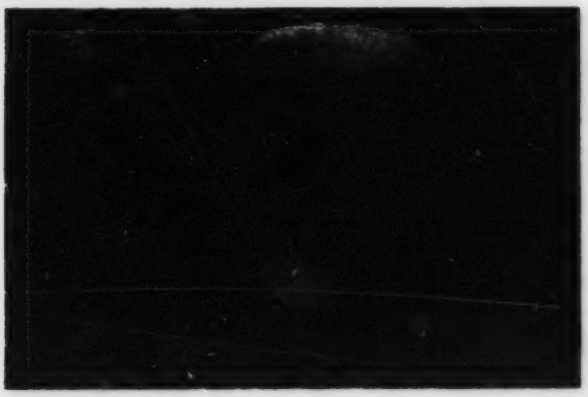


Figure 22. Ice widge polygons in tundra peat. (GSC 203121-F)

Figure 23. Small palsa in grassy fen near Churchill. Photo taken in 1978. This palsa has since ruptured and the ice core has degraded. (GSC 203121-J)

Figure 24

A. Vertical and, **B.** oblique photos of coalesced peat plateaux and surrounding fenlands. (NAPL A1421S-97 near Port Nelson and GSC 203992-Y near Churchill)

vegetation cover is limited, and near the coast where peat has had little time to accumulate. These areas are extremely poorly drained, and ephemeral ponds are common. Seasonal thawing extends through the peat into the mineral substrate.

THE STRATIGRAPHIC RECORD

Sediment sequence

Exposures along the Seal, North and South Knife, Churchill, Little Churchill, Beaver, Owl, Deer, and Nelson rivers reveal a sequence of till sheets separated by fluvial, lacustrine, and organic units. The sections record events relating to the waxing and waning of ice sheets centred in Keewatin and Labrador or Hudson Bay, and to the interaction between these two ice masses through time. They also record major interglaciations. Sections along the Seal River record Keewatin ice events, whereas those along Little Churchill and Nelson rivers primarily record events related to ice flow from the east (Fig. 25). Sections along North and South Knife rivers lie within the zone of convergence of the two main ice masses and record shifting ice flow patterns, as evidenced by till sheets separated in places by sandy layers.

The stratigraphy described in this section is based on the interpretation and correlation of units according to their stratigraphic position relative to organic marker beds, and to their physical characteristics (lithology, texture, colour, weathering, and sedimentary structures). More than 280 sections were examined. The location of key sections used to compile the composite stratigraphic sequence is shown in Figure 26; these sections are described in the Appendix, and a few of them are summarized in Figure 27. The stratigraphic framework is best documented along the Nelson estuary, where most key units are present in one section, and where pollen and beetle studies on the interglacial units have been carried out. Consequently, the sections in that area are reported more fully in the Appendix and in Dredge et al. (1989, 1990). Joint field work by the authors and E. Nielsen (Manitoba Energy and Mines) indicates that many of the units described below correspond to those already described along Nelson River near Gillam (Nielsen et al., 1986). The Nelson River nomenclature is therefore used in this report.

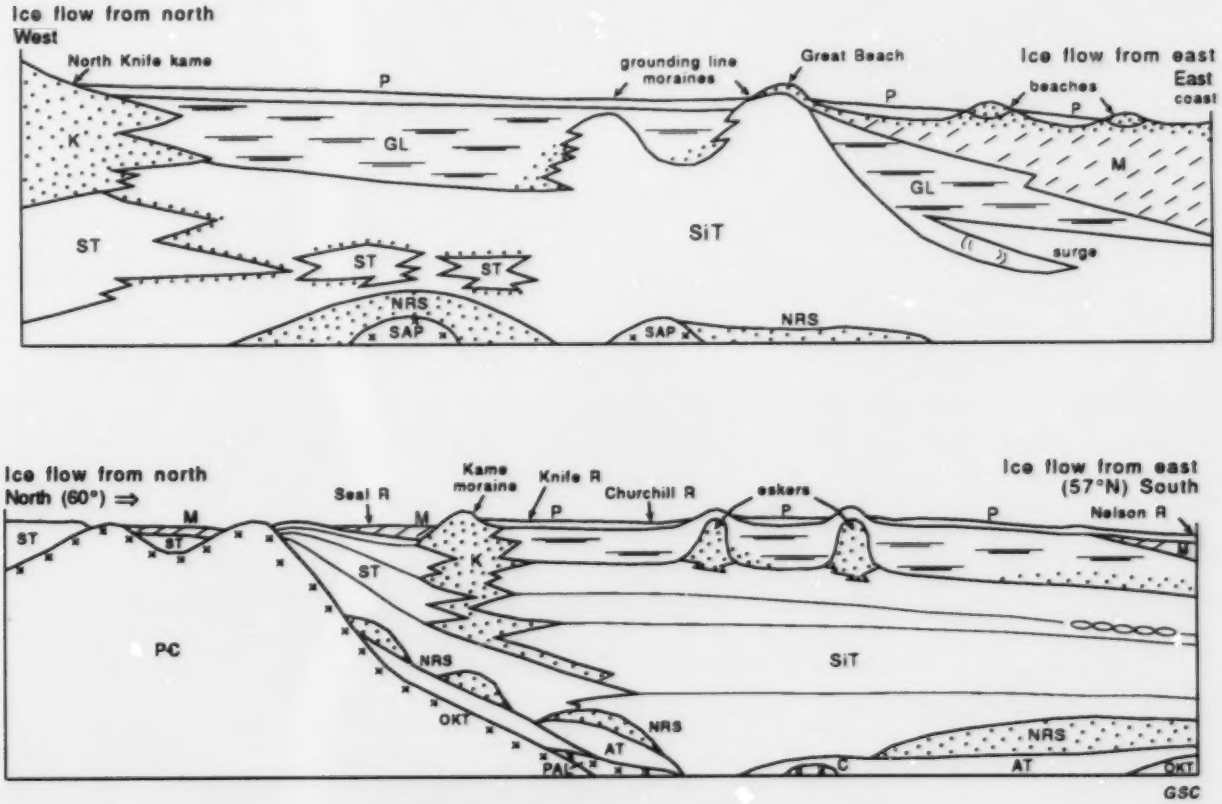
The stratigraphic sequence outlined in this section consists of saprolite, two old tills, an interglacial sequence, a sequence of olive-grey tills separated by sand beds, brown till grading to waterlaid sediment, glacial lacustrine deposits in places overridden by till, and marine, fluvial, and estuarine sediments. The units are described from oldest to youngest. Those stratigraphic units that form surficial units have already been described. The descriptions in this section are confined to details that relate to their stratigraphic interpretation, or to aspects only observed in sections.

Saprolite

Gruss and saprolite derived from the in situ weathering of quartzose granitic metasediments and diorites are exposed along North Knife River over about 15 km at about longitude 96°30 west (loc. 5, Fig. 26). The thickness of weathering is about 7m. Where the bedrock has been reduced to gruss, it consists of irregular hackly gravel-sized fragments of rotted diorite. In others a saprolite with a soapy to cheese-like consistency has developed, having koalin as the most abundant clay mineral. Strong soil hues are characteristic, namely white, yellow, orange, and blue-green. The saprolite may have formed either during a major nonglacial interval in the Quaternary era or even earlier.

Harts till: old Keewatin till

The oldest till, exposed as the basal unit of the Harts Creek section (loc. 26), may be the same as that exposed at low tide along the Nelson River estuary. This greyish till has a sandy silt texture at Harts Creek, consisting of about 34% sand and granules, 55% silt, and 11% clay. About 59% of the pebble-sized clasts and 32% of the granules are of Paleozoic lithology. The matrix is 33% carbonate. The age of this till is uncertain, but its stratigraphic position below the Amery till suggests that its age is Illinoian or older. Its relatively high content of Precambrian shield clasts and fairly sandy texture



Sand and gravel	*Amery till* ... AT	*Paleozoic rock* ... PAL
Silt	*Cretaceous rock?* ... C	*Precambrian rock* ... PC
Silt and sand	*Glaciolacustrine deposits* ... GL	*Peat* ... P
Rock	*Kame moraine* ... K	*Sandy till (Keewatin)* ... ST
	Marine deposits ... M	*Saprolite* ... SAP
	Nelson River Sediments ... NRS	*Silty till (Hudsonian/Labradorian)* ... SiT
	Old Keewatin till ... OKT	

Figure 25. Schematic stratigraphic transects across northeastern Manitoba, showing relationships between principal stratigraphic units.

compared to the other tills in the Nelson River area suggest that this till has either a northern (Keewatin) or a southern (Patrician) provenance. On the basis of its lithology, the unit is tentatively correlated with the Sundance till of Nielsen et al. (1986), which outcrops near Gillam. Miniature crag and tail features on the bedrock near Gillam, and specific lithologic indicators, suggest a southerly ice flow. The Harts till is therefore assumed to be also of Keewatin provenance. The texture and lithology differ somewhat from the till near Gillam, however, because both Shield and carbonate bedrock lie to the north (up-ice) of the Harts Creek site, whereas Precambrian bedrock is the principal rock type north of Gillam.

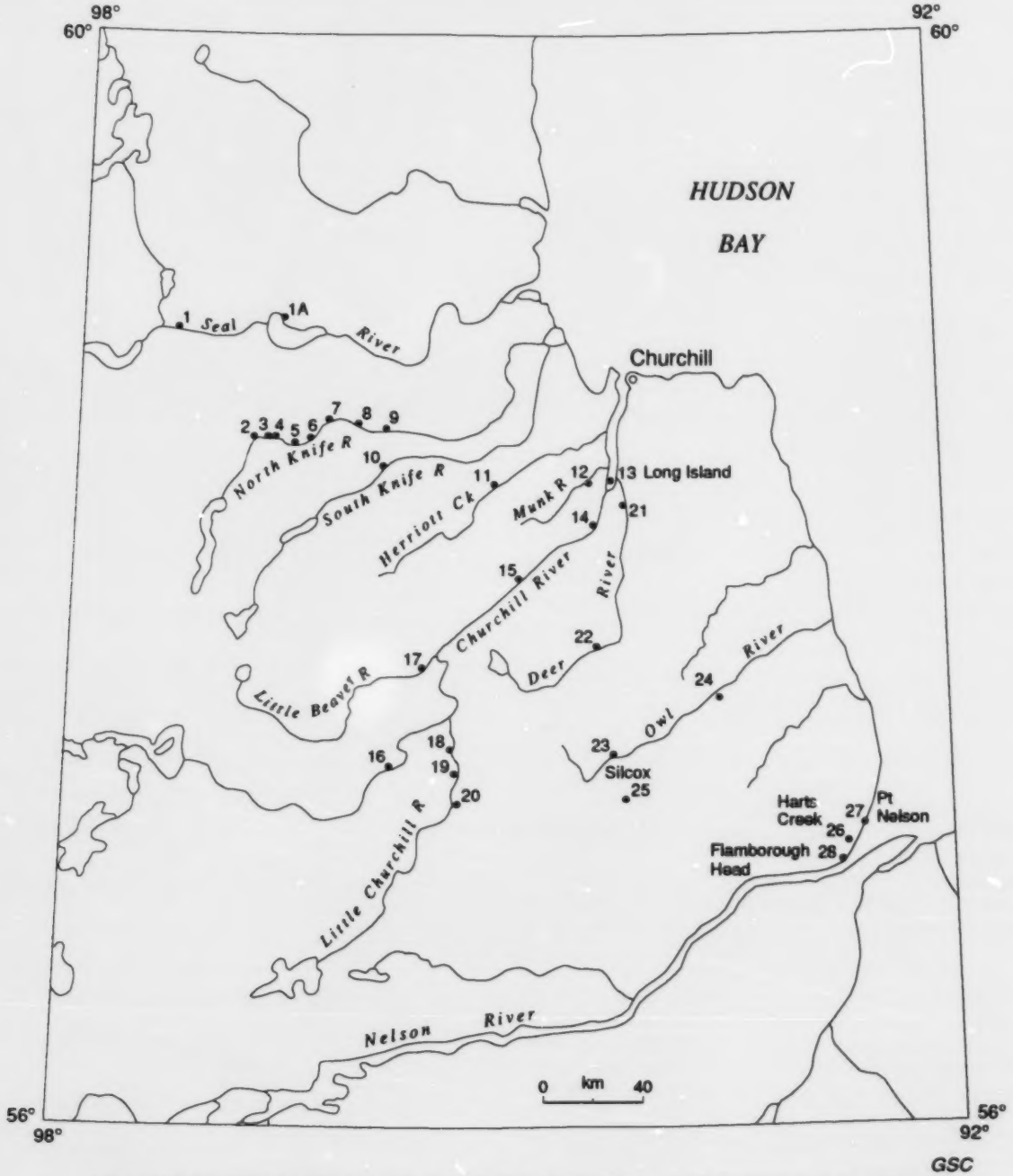


Figure 26. Location of sections used to compile the stratigraphic record. Numbers refer to section descriptions in the Appendix and in Figure 27.

Amery till

The Amery till is exposed along an 8 km stretch of the Nelson estuary (loc. 27) west of Port Nelson, where it forms the basal 2 m and more of the bluff. It is also recognized as the lowermost till at Mountain Rapids (loc. 16) and at Limestone Rapids along Churchill River (loc. 14). The Amery till is overlain either by organic sands and silts, or by fluvial gravels; the upper contact with these sediments is undulatory and erosional. The till is grey to pale brown, blocky, and extremely compact. Joints are widely spaced and have irridescent surfaces that are stained a deep red. The till is relatively stony, and only about 20% of the clasts are granitic, even where the till is underlain by granitic bedrock. The carbonate content of the matrix is 20 to 40%. The till is silty with a substantial clay content. The average texture is 32% sand, 45% silt, and 23% clay. The clayey silt texture, carbonate content, and low content of Precambrian clasts relative to the underlying till and bedrock suggest that this till was deposited by ice flowing westward. If this were the case, then the Precambrian clasts either were reworked from the underlying Keewatin till or unrecognized interglacial sediments, or they were derived from source rocks in central Quebec. The till has a normal remanent magnetism (R. Barendregt, personal communication, 1987). It is in the same stratigraphic position as the Amery till described by Klassen (1986) and Nielsen et al. (1986). Because of its stratigraphic position below a major interglacial unit this till is considered to be of Illinoian age.

Nelson River sediments

Major subtill deposits of gravel, sand, silt, and organics up to 5 m thick are exposed along Seal (at loc. 1A), North Knife, Churchill, and Nelson rivers. Along North Knife and parts of Seal rivers the gravels outcrop at river level; along Churchill and Nelson rivers they are exposed higher in the sections so that the upper and lower contacts are visible. The lower contact with Amery till undulates and is erosional. The upper contact of gravels or silts with the overlying till is generally

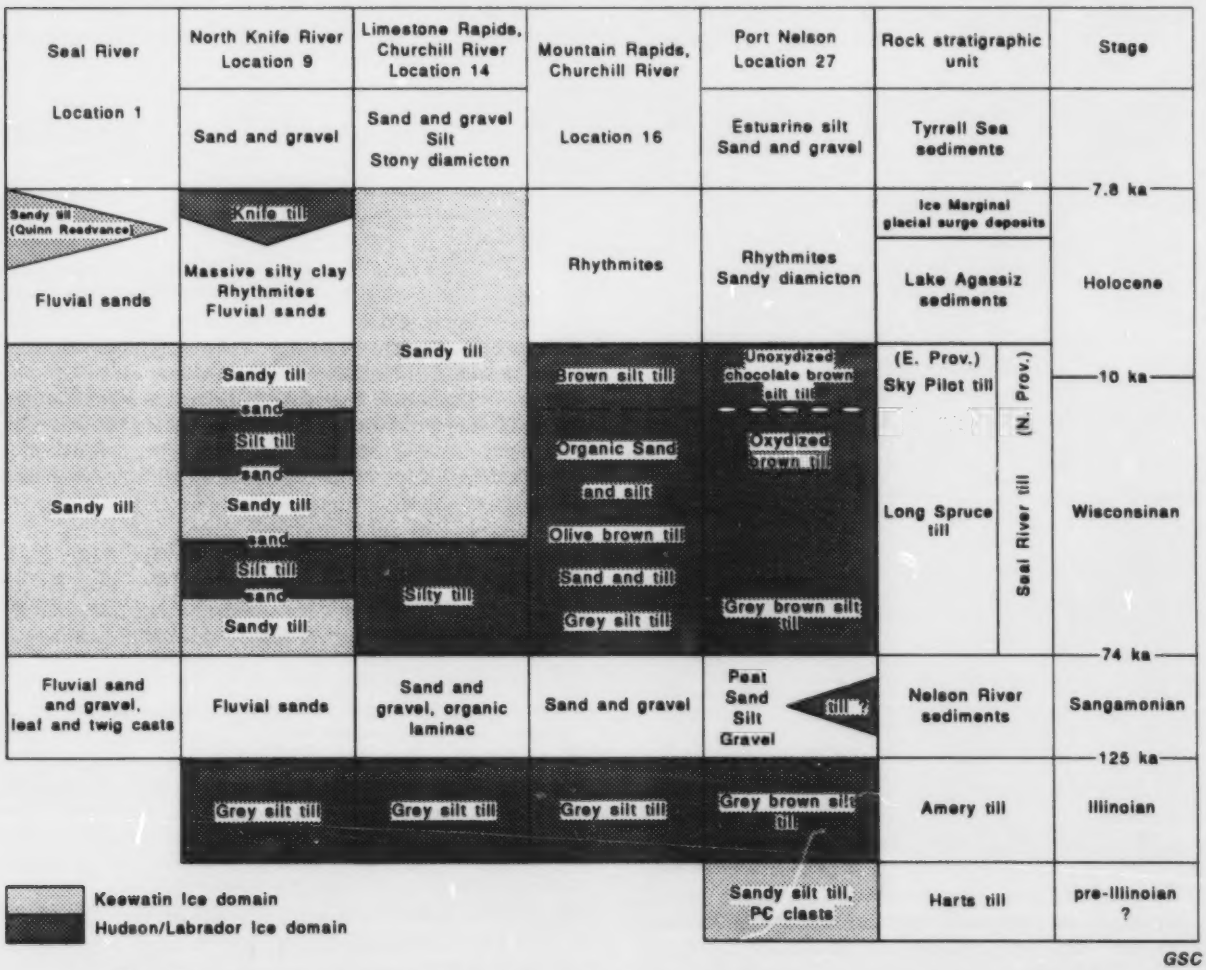


Figure 27. Representative sediment sequences in northeastern Manitoba, showing various tills and interglacial units.

sharp, but contortions and folds in the upper decimetre of the sediments, and displaced slices of gravel or silt in the lower part of the overlying till (e.g., Mountain Rapids on Churchill River, and at Port Nelson) represent glaciotectonic deformation in the upper part of the unit.

In many sections only the sand and gravel units occur; in others, they form the basal part of a more extensive sequence. Typically the gravel is very compact and consists of rounded cobbles and pebbles packed into a silty matrix. The unit is commonly massive, but where crossbedded sands are present, bedding indicates current flow similar in direction to present. On Seal River (loc. 1A), the gravels contain casts of leaves, twigs, woody peat, and moss (Taylor, 1961). Although some of the massive units could possibly be glaciofluvial deposits associated with retreat phases of the Illinoian glaciation (Amery till), the crossbedded units are fluvial. Current directions and base levels required for streamflow indicate that Hudson Bay was free of glacial ice, and that base level was similar to present. In many places, the upper part of the gravels are rust-coloured and cemented. The oxidation may represent the lower part of a paleosol, although a groundwater effect cannot be ruled out.

Figure 28. Sand, organic detritus and peat from Sangamonian interglacial beds at Flamborough Head, Nelson Estuary southwest of Port Nelson. (GSC 204735-B)

Along Nelson River, and sporadically in other exposures, the gravel unit is overlain by 2 to 3 m of medium to fine sand, having planar beds or ripple drift features, and by horizontally stratified silt. These sediments were deposited in shallow water lacustrine or fluvial environments under low energy conditions. All sediments have a normal remanent magnetism (R. Barendregt, personal communication, 1987). At Flamborough, spruce twigs, organic pods, and layers of platy compressed peat are also present (Fig. 28). The peat unit is a bog deposit whereas the overlying organic stringers are transported elements. Pollen from the silt and sand units at Port Nelson show a predominance of spruce pollen; pine pollen is present in smaller amounts. Spruce was probably the predominant tree type. Nonarboreal pollen was also abundant throughout the profiles. Beetle, weevil, and spider remains, as well as the pollen assemblage indicate a boreal forest environment near the forest-tundra boundary. Pollen profiles from the equivalent unit at Limestone Rapids on Churchill River farther north indicate cooler tundra conditions dominated by willow, alder, grasses, and moss, with lesser amounts of spruce. The assemblages indicate conditions similar to present at their respective sites. The lack of evidence for climatic changes within the profiles suggests that the sediments are incomplete records of the intervals they represent.

The origin of the organics in the sand encountered high in the section at Mountain Rapids (loc. 16) presents a problem. They appear as small diamictic inclusions, small rounded nodules, and discrete peaty fragments. The dark inclusions are dominated by spruce pollen, with lesser pine, birch, and alder. The organic nodules are predominantly grass, sedge, and herbs, with minor pine. The peat fragments are dominated by birch. The pollen spectra in the inclusions are similar to those in the interglacial unit on Nelson River; the other samples are not analogous, although they still represent northern boreal forest to tundra environments. Mott (Dredge et al., 1990) considered all the organics at section 16 to be reworked "clasts" and transported detritus, presumably reworked from organic deposits stratigraphically equivalent to the lower gravel.

Small salix twigs at Mountain Rapids (loc. 16) have been dated to >32 000 BP (GSC-3074), and a twig at Limestone Rapids (loc. 14), to >19 000 BP (GSC-3074). High-pressure radiocarbon dates on wood from equivalent units in northeastern Manitoba beyond the field area gave nonfinite ages greater than 48 000 (GSC-4420, 4444, 4471). On the basis of stratigraphic position, paleoecological indicators of climates similar to present, conditions requiring an ice-free Hudson Bay, and similarity of the sediments and organics to the Gods River sediments of Klassen (1986), the Nelson River sediments of Nielsen et al. (1986), and the Missinaibi beds of Skinner (1973), these sediments are assigned to the Sangamon Interglaciation. (The term is used here to denote both relatively warm periods in the Sangamon Stage). Because the pollen profiles do not record any changes of climate, it is concluded that only a small part of the interglaciation is recorded in the preserved sediments.

Tills of the Wisconsin Glaciation

The Wisconsin Glaciation is represented by tills deposited by ice flowing from two distinct source areas, one lying to the north in the districts of Keewatin-MacKenzie, the other lying to the east in central Quebec or Hudson Bay. In the type areas the two tills are distinctive. The Keewatin tills are very sandy, have low clay contents and are composed of granitic lithologies. In contrast, the Hudson-Labradorean tills are silty and have substantial quantities of clay; clasts are predominantly carbonates, derived from Paleozoic limestone and dolomite. The differences between these two types of till become less distinct where southward flowing ice sheets originating on the Shield crossed onto Paleozoic rocks or older calcareous tills, and where westward flowing ice sheets either crossed from carbonate terrain to granitic terrain, or incorporated older Keewatin till. Typical Keewatin till outcrops on Seal River, and typical Hudson-Labradorean till outcrops along Nelson River. Tills of intermediate composition and texture are common in the central part of the map area.

Seal till (Keewatin provenance)

Olive-grey tills of Keewatin provenance are exposed along Seal River, where they are the only tills, and interfinger with Hudson and Labradorean tills on Churchill and North Knife rivers (Fig. 25). They directly overlie bedrock in some places; in others they overlie interglacial sediments. They form the uppermost till sheet north of North Knife River and west of South Knife Lake (long. 97°W) and lie below Labradorean-Hudson tills as far south as Churchill River. The till is commonly 2 to 5 m in thickness. Tills of Keewatin provenance are much coarser and much less calcareous than Hudson tills. They are sandy to bouldery. In typical areas along Seal River, where the tills overlie Precambrian terranes, the texture is typically 65% sand and granules, 30% silt, and 5% clay. Clasts are subangular and are of granitic lithology. Carbonate pebbles are absent in the northern part of the area, and carbonates constitute less than 3% of the matrix. The tills become finer textured and contain more carbonate where glaciers have overrun old calcareous tills or Paleozoic bedrock. The till is loose to compact and exhibits numerous small poorly defined crossbeds and ripple drift structures throughout, particularly around boulders. Pebble fabrics commonly show no consistent orientation. We favour a meltout origin for parts of the till sheet having these structures.

Tills of Hudson-Labradorean provenance

Silty calcareous brownish-grey tills overlain by a distinctive brown till form a unit that is up to 25 m thick at many localities. In their type localities along Nelson River, the tills of Hudson-Labradorean provenance are distinguished from Keewatin tills on the basis of their clayey silt matrix and predominance of carbonate lithologies. They constitute the uppermost Wisconsin till sheet south of North Knife River and east of South Knife Lake (long. 97°W). Between longitudes 97°W and 99°W they have been observed in section below Keewatin till; between North Knife and Churchill rivers they interfinger with sandy Keewatin tills but form the surface till sheet.

The lower contact of this till with underlying Nelson River sediments is generally erosional and abrupt, but at Port Nelson the top of the interglacial unit has been incorporated into the lower part of the till, as thin thrust slices, and as brecciated fragments of silt. The tills are conformably overlain by glaciolacustrine deposits, and in many places the normal till grades into a waterlaid facies.

Long Spruce till. The grey to brown-grey till can be subdivided into a number of sheets, separated by sand beds, but rarely distinguishable from one another on the basis of texture or lithology. In a few places, the lower till units are more compact and stonier than the upper ones, but this relationship is not regionally consistent. The stack of greyish tills are blocky, hard, compact, and have oxidation rinds 2 to 3 mm thick along joint surfaces; they are fissile. Grain size analyses show that the tills are roughly 25% sand and granules, 45% silt, and 30% clay. Clasts are generally subangular. The pebble fraction consists of 20 to 30% undifferentiated Precambrian rock types and 70 to 80% carbonate. There is 50 to 70% carbonate in the granule fraction. In the lower units greywacke is present but consitutes less than 1% of the pebble fraction and up to 5% of the granules. There is 30 to 35% carbonate in the matrix. The tills contain shell chips of *Hiatella arctica* with total isoleucine ratios of 0.10 to 0.15.

Regional variations in these tills were produced as glaciers slid over different rock types. As well as changes in granitic and carbonate clast content, black tills contain shale particles at several sites (loc. 18, 20) in the west central part of the map area. The black colour and the shale particles are thought to derive from an unmapped Cretaceous outlier centred at about 57°15′N and 95°15′W.

At many sections (e.g., loc. 10, 12, 16, 18, 19, 20, and 26) one or more sand beds, each 11 to 30 cm thick, separate the grey tills. At Port Nelson intratill sand beds are traceable as continuous beds for more than 1 km; in contrast, along Knife and Churchill rivers, the beds cannot be traced from one section to another, and their number varies from place to place. The origin of these sand units, which is important to deciphering the glacial history of the area, is somewhat problematic. Klassen (1986) and Andrews et al. (1983) have inferred similar units to be interstadial nonglacial deposits associated with the deglaciation of Hudson Bay. However, the units lacked well-defined fluvial cross-bedding and current structures that might indicate flow towards Hudson Bay. The units are barren of fossils or other organics; the number of beds varies from site to site; the sand is commonly massive and poorly sorted; and the sand beds are commonly intercalated with, or grade into, till at both their upper and lower contacts. Field relationships suggest that the sands are intratill deposits, which originated below or within the ice sheet. They may have been deposited from melting layers within the ice sheet and subsequently let down as part of a melt-out till. Alternatively, because they are most abundant

in the area between North Knife and Churchill rivers, where lithologic variations in the till sheets above and below the sand beds reflect the influence of both the Keewatin and Hudson/Labradorean ice masses, they may be interlobate glaciofluvial deposits associated with either localized subglacial sheet flow or subglacial channelled flow. Such meltwater activity would be prevalent in the central part of the map area, which was the zone of convergence of the Keewatin and Hudson ice masses. The sand beds would occupy different levels in the till sequence and different geographic locations as the zone of confluence shifted over time.

The grey tills are considered to be of eastern provenance because of the high percentage of carbonate in the clast and matrix fractions, the correspondingly high clayey silt content, the incorporation of marine shells from Hudson Bay, its east-west fabric and orientation of striae on bedrock surfaces along Churchill River. The Precambrian clasts may derive from the reworking of old Keewatin tills or from sources (old or contemporaneous) in central Quebec. The occurrence of greywacke erratics from the Omarraluk Formation in eastern Hudson Bay suggests that the lowermost part of the till may have been emplaced by Labradorean ice, or may have resulted from the incorporation of Labradorean material by Hudson ice. On the basis of their stratigraphic position, the grey tills are considered to span the interval of the Early and Middle, and possibly part of the the Late Wisconsinan.

Sky Pilot till (brown till). The grey beds are overlain by 2 to 6m of distinctive chocolate brown till, which in places grades upwards into glaciolacustrine deposits. In some places the brown till is separated sharply from the underlying grey tills by a striated boulder pavement; elsewhere the contact is gradational. The till has a low to moderate compaction and breaks into hackly fragments rather than into joint blocks. At Port Nelson, the brown till can be separated into lower and upper unoxidized units. The carbonate content is similar to that of the grey tills, but the brown till has 5 to 10% more clay, making it texturally finer and slightly more plastic. Like the grey tills, the brown till also contains shell chips. The brown results from the incorporation of red-brown siltstone from the Kenogami Formation in Hudson Bay. In the western part of the map area (e.g., loc. 15), auger cores indicate that the upper part of the brown till is loose and clayey. This facies is considered to be the waterlaid till deposited from below an ice ramp as the Hudson ice mass receded against Lake Agassiz.

In relation to overlying glaciolacustrine units, the compact brown till is considered stratigraphically to be of Late Wisconsinan age, and the loose uppermost facies to be early Holocene. The boulder pavement, the distinct change from grey to brown and the incorporation of red siltstone suggest a change in the ice trajectory of the Hudson ice mass during the latter part of the glaciation.

Summary of Wisconsinan stratigraphy

Sections from northeastern Manitoba indicate that Labradorean or Hudson, and later Hudson ice flowed westwards across the southern part of the map area, while Keewatin ice flowed southward across the northern part. The two ice sheets converged in the central area; interfingering of tills over a considerable area indicates that the position of convergence shifted during glaciation. Evidence suggests continuous ice cover during the entire Wisconsin glaciation; sand beds are considered to be intratill deposits having englacial or subglacial origins. An alternative to this interpretation has been considered and discussed in Dredge et al. (1986).

The grey and brown tills in the map area correspond to the Long Spruce and Sky Pilot tills of Nielsen et al. (1986), although he does not mention the glaciolacustrine facies in this context. The grey tills further correspond in part to the Wigwam Creek formation of Klassen (1986); however, Klassen did not recognize the brown till, although it has been reported in areas south of Hudson Bay in northern Ontario (McDonald, 1969; Dredge and Cowan, 1989). In addition, Klassen interpreted the sand units in the grey till sheet as interstadial deposits indicating several ice-free periods during the Wisconsin Stage. Our interpretation is that the sand beds are subglacial, and that ice continuously covered the area during the Wisconsinan Stage.

Lake Agassiz sediments

Glaciolacustrine deposits, consisting of subaquatic turbidite sand, varved silt and clay, and massive clayey silt, were deposited into glacial Lake Agassiz. As the Keewatin and Hudson ice masses receded, the margin of this water body migrated east and north. The sequence of deposits indicates steadily retreating ice. The lower contact of this unit is erosional where meltwater from the base of the ice scoured the till surface, but in most other localities it is gradational to the waterlaid facies of the brown till. The glaciolacustrine sediments are overlain by marine sediments below an elevation of 150 m but above that elevation, form the principal surficial material over a vast area.

The glaciofluvial facies (Fig. 19) is exposed at Port Nelson as a massive, pebbly diamictic sand about 3 m thick, which is traceable as a horizontal unit over more than 1 km. At loc. 9 along North Knife River a similar unit consists of crossbedded sand with structures indicating current flow westwards. This unit is likely an ice proximal sediment deposited where meltwater from the base or surface of the ice sheet debouched into the glacial lake and generated a turbidity current (Dredge and Nielsen, 1987b). The crossbedded sands grade upwards into planar beds and then to rhythmites.

The varve facies is best exposed along North and South Knife rivers, where it reaches a thickness of 7 m and consists of more than 150 couplets of brick-red clayey and grey silts. The couplets are coarsest and thickest (15 cm) at the base of the section and become finer and thinner (1 cm) above. The top of the sequence has been truncated by overriding ice.

The uppermost glaciolacustrine facies consists of either massive, uniform brown silt or clayey silt of moderate plasticity. The average texture is 19% sand, 63% silt, and 18% clay. The material has a low stone content but contains

granules of hard clay, which might be rip-up fragments. The calcareous sediment has carbonate contents ranging from 18 to 46%.

The transition from fluvial beds, rhythmites, the thinning and fining upward sequence, and cap of massive clay indicate steadily retreating ice and progressive distance from currents and sediment sources. The Lake Agassiz sediments immediately precede the marine episode in northeastern Manitoba. Dates on marine shells indicate that the lake drained between 7800 and 8200 years ago, so the sediments are Holocene in age.

Knife till (Cochrane equivalent)

A relatively thin till unit, 0.6 to 1.5 m thick, sharply truncates the glaciolacustrine deposits on uplands near North Knife River (loc. 9). The till is unoxidized, of low compaction, and breaks apart into small peds. The average texture is 17% sand, 73% silt, and 11% clay; carbonates account for 23% of the fines. The lower part of the till consists of reworked brown glaciolacustrine sediments. The original bedding in the varves is highly contorted and overturned and includes angular blocks of stratified clay. This till grades upwards into grey or brown gritty calcareous silt till with some stones. The sporadic occurrence of this till, its internal composition, and its association with surface iceberg scour marks suggest that it was produced by surging of an unstable ice margin into the glacial lake. This till is similar in nature and origin to the Cochrane Till in northeastern Ontario, and is probably roughly contemporaneous with the Quinn Lake readvance described in northwestern Manitoba (Dredge et al., 1986).

Glaciomarine unit

Glaciomarine deposits are limited to areas north of Owl River and to elevations below 90 m (e.g., loc. 13, 21) and underlie silty marine sediments. The deposits are a grey calcareous diamicton till-like in texture (36% sand and granules, 46% silt, and 18% clay); 22 to 48% of the fine fraction is carbonate. About half the clasts in this stony unit are carbonate. The massive, crumbly unit, usually 1 to 4 m thick, has low compaction and contains marine shells.

The genesis of this unit is unclear. Either it could be a true glaciomarine deposit dropped from a glacier and associated with the break-up of the major ice sheet in Hudson Bay, or it could be a diamicton deposited under sea ice containing substantial quantities of ice rafted debris. In the latter case, it should be classed as a marine deposit and may not be substantially similar to materials being deposited offshore in Hudson Bay today.

Tyrrell Sea sediments

Lee (1960) gave the name Tyrrell Sea to the postglacial sea that occupied the Hudson Bay basin. Deposits relating to this sea are found in section below maximum elevations of 130 m in the southern part of the map area and 180 m in the north. They constitute the main surficial material (excluding peat) over much of northeastern Manitoba. The sediments thicken from 1 to 2 m near marine limit (e.g., loc. 23, 25) to more than 8 m in sections at the coast. The marine sediments consist of three facies: 1) a coarsening upwards sequence of grey clay and silt, commonly fossiliferous, with carbonate contents ranging from 17 to 47% and typical textures of 40% sand, 47% silt, and 13% clay; 2) a shallow water facies consisting of well sorted, stratified littoral sand, generally less than 2 m thick; and 3) a laminated silt with organic blebs, which overlies the littoral facies. These are thought to be tidal deposits.

The marine sediments are fossiliferous. Shells dating 7750 ± 140 BP (GSC-3070) were recovered from North Knife River at an elevation of 110 m; they provide a minimum age for the beginning of the Tyrrell Sea episode. The date is similar to those reported from Nelson River near Long Spruce dam. Shells there were dated to 7760 ± 80 BP (GSC-3916) (Nielsen and Dredge, 1982) and 8200 ± 300 BP (BGS-813) (E. Nielsen, personal communication, 1985) by two different laboratories. The Tyrrell Sea sediments correlate with other marine deposits throughout the Hudson Bay lowlands.

Alluvium and peat

The uppermost stratigraphic units are alluvium and peat. Alluvial sands with rounded gravel are minor units confined to present and former river channels. The thickest deposits occur along the lower part of Churchill River (Loc. 13, 14, 21).

Peat is a major surficial deposit in this area, mantling most of the inorganic deposits south of Seal River. Its physical character has been described in the section on surface materials.

Regional correlations

The regional correlation of units (Fig. 29) is based on the position of units relative to organic-bearing marker beds and on the lithic character of the tills. We assign all organic units to the Sangamonian Stage. However, Dredge and Cowan (1989) discussed potential problems with assuming that all organic units belong to the same interglaciation.

The Nelson River sediments and associated interglacial deposits are linked with the interglacial beds along Nelson River near Gillam (Nielsen et al., 1986). They correlate stratigraphically with the Gods River sediments of Klassen (1986) and the Echoing River sediments of Dredge and Nielsen (1985) within northeastern Manitoba, and with the Missinaibi Formation of Skinner (1973) in northeastern Ontario on the basis of their stratigraphic position, because only one sub-till organic unit is exposed at each section, and because they show paleoenvironmental similarities. They are also correlated with the Fawn and Severn River gravels in northwestern Ontario (McDonald, 1971). These major fluvial units indicate currents flowing northwards to lower base levels in an open Hudson Bay. All these units have been assigned to the Sangamon Interglaciation and correspond to the time interval between 74 000-125 000 BP. This correlation differs somewhat from that proposed by Shilts (1984), in which the Severn and Fawn River gravels are considered to be Wisconsin interstadial deposits.

The main till below these marker beds corresponds to the Amery Formation of Klassen and the Amery till of Nielsen et al. (1986) and has been assigned an Illinoian age; it may be the same age as the till III of Skinner.

The older till at Harts Creek is of indeterminate age but is older than the Amery till. It may correlate with Nielsen's Sundance till and be age-equivalent to, but of different provenance from, Skinner's till III; the Harts till is of Keewatin provenance, whereas Skinner's till is Labradorean.

The greyish tills above the Nelson River sediments correspond to the Long Spruce till of Nielsen et al. (1986) and the Wigwam Creek Formation of Klassen (1986) in northern Manitoba, and the grey unit within the Adam Till of Skinner (1973). However, the contained sand beds here are considered to be intratill formations, whereas Klassen interpreted them as interstadial deposits. The upper brown till corresponds to the Sky Pilot till of Nielsen et al. (1986), the regional brown till in northern Ontario reported by McDonald (1968, field notes), and the brown unit corresponding to Adam Till/Matheson till in the James Bay area. The distribution of brown till and its lithology indicate ice flow out of Hudson Bay. The Lake Agassiz deposits are considered to be time-equivalent to the Friday Creek sediments of Skinner. This correlation differs from that proposed by Shilts (1984), who interpreted that unit as a mid-Wisconsinan interstadial deposit.

The Kipling Till overlying Skinner's Friday Creek sediments is here correlated with the Cochrane Till of Hughes (1965) in the eastern Hudson Bay lowlands; it is considered to be roughly time-equivalent with the Knife till in the western Hudson Bay lowlands. These three tills were produced by the same kind of event. The Knife till is considered to be the product of a short-lived ice marginal surge into the glacial lake, rather than a Wisconsinan stadial ice advance. The Tyrrell Sea deposits are recognized throughout the lowlands.

GLACIAL AND POSTGLACIAL HISTORY

Ice flow indicators

Based on many striation measurements, and by intuitive insight, Tyrrell (1898 a and b, 1913a) proposed that the Laurentide Ice Sheet had three gathering grounds or centres of growth – the Keewatin, Patrician, and Labradorean centres. Data from northeastern Manitoba, together with new findings relating to the broader structure of the North American ice sheet complex (Dyke et al., 1982; Dyke and Prest, 1987), essentially confirm Tyrrell's concept that the Laurentide ice sheet was composed of a number of interacting, but semi-independent ice masses. These growth centres affected northeastern Manitoba. Keewatin Ice, centred in the central part of the districts of Keewatin and Mackenzie (Fig. 1; Dredge et al., 1986, fig. 28), flowed

	NE Manitoba (this report)	Gillam (Dredge and Nielsen, 1985) (Nielsen et al., 1986)	Gods River (Klassen, 1986)	NW Ontario (McDonald, 1971)*	Moose River (Skinner, 1973)*
Present	Tyrrell Sea sediments	Tyrrell Sea sediments	Tyrrell Sea sediments	Tyrrell Sea sediments	Tyrrell Sea sediments
7.8 ka	Knife till ←	L. Agassiz sediments	L. Agassiz sediments	? soft brown till ↓	Kipling Till ↙
Holocene	L. Agassiz sediments			glacio-lacustrine silt	Friday Cr. Sediments
10 ka	Seal till ↓ / Sky Pilot till ↗ / Long Spruce till ←	Sky Pilot till ↗ / Long Spruce till ←	Wigwam Ck formation / Till ↙ / sand / Till ↙ / sand / Till ↓	compact brown till ^ / grey tills ↙	brown / Adam Till(s) ↙ / grey
Wisconsinan 74 ka					
Sangamonian	Nelson River sediments	Nelson River sediments	Gods River sediments	Fawn, Severn River gravels	Missinaibi Fm
125 ka					
Illinoian	Amery till ←	Amery till ↗	Amery till ↙	Grey till ↓	Till III ↙ sands / Till II sands / Till I — ? Bell Sea
	Harts till / Old Keewatin till ↓	paleosol / Sundance till ↓		Grey till	

*In this stratigraphic correlation, the ages of McDonald's and Skinner's units differ from the original interpretation. These changes are discussed in Dredge and Cowan (1989).

Ice flow direction . . . . . ↙

GSC

Figure 29. Correlation of major lithostratigraphic units across the Hudson Bay lowlands.

southwards and, at some time, reached as far south as Iowa. During the last glaciation, Labradorean ice crossed the southern part of the region, and then Hudson ice spread out from a centre over Hudson Bay and reached as far west as Lake Winnipeg and southwestern Manitoba.

Northeastern Manitoba lies along the convergence between the Keewatin and Hudson/Labradorean ice domains. The northernmost part of the region was successively covered by southward flowing Keewatin ice, whereas the Nelson River area was affected mainly, but not exclusively, by westward flowing Labradorean and Hudson ice. The intervening area experienced flow from both ice sheets. The stack of till sheets and other ice flow indicators record the sequence of glacial movements from these centres and, therefore, also the changing dynamics of these interacting ice masses.

A wide variety of features and landforms indicates the direction of successive glacial advances and final retreat of the last ice sheet. However, for northeastern Manitoba the best indicator of ice flow is the texture and clast composition of the till and matrix carbonate content, which serve to identify major regional ice flow patterns and to indicate ice streams within the regional pattern (Dredge, 1988b). Erosional markings, observed in only a few places in this region, are striae, grooves, and roches moutonnees, which give the direction, and sometimes the sense, of ice flow. The sequence of flow is recorded in crosscutting relationships. Ice moulded bedforms, such as flutes and drumlins, also show directions of ice flow, although these features may represent flow only near ice margins. Features such as moraines and eskers provide indirect information about ice flow directions, particularly during glacial retreat. All these indicators have been discussed previously in the section on surficial materials. The directional data are summarized here as Figure 30.

Pre-wisconsin glaciations and the Sangamon interglaciation

The oldest materials younger than Paleozoic are the saprolites exposed along North Knife River. These strong-hued, extensively kaolinized deposits may either be pre-Quaternary in age or may belong to an early Quaternary period of intense weathering.

The oldest ice flow recorded in the region came from the north and deposited the Harts till. The oldest striae at Churchill, oriented 130° or 310°, may have been produced by the same glacial event (Fig. 31A). If this ice flow were the same as that producing the old striae on Chekask Hills in northwestern Manitoba (Dredge et al., 1986), then the centre of outflow may have been in the District of Mackenzie. Although the southern extent of this glacial advance is unknown, the presence of till of northern provenance at least as far south as Port Nelson indicates that the northern ice centre was more extensive and more vigorous than its Wisconsinan Keewatin counterpart. The age of this early southerly ice flow is unknown; however, the stratigraphic position of the Hart till suggests an age of "Illinoian" or older (i.e., older than oxygen stage 8).

During a subsequent glaciation (Fig. 31B), ice flowed westwards across the region from a centre in central Quebec (Labradorean centre). It deposited a silty, calcareous till (Amery till) containing Quaternary foraminifera and shell fragments derived from Hudson Bay, as well as distinctive Proterozoic erratics from eastern Hudson Bay. This till extends at least as far west as Mountain Rapids. As the till directly underlies a major interglacial deposit assumed to be Sangamonian, an Illinoian age has been assigned to this Labradorean glaciation.

During a major interglaciation, river gravels, sand, peat, and thinly bedded silt were deposited, indicating that Hudson Bay was free of ice (ice in Hudson Bay would have held up a glacial lake in this area). Because fluvial gravels outcrop near sea level at Port Nelson, base levels were at least as low as present. At the time when the peat developed, and when the alluvial and pond silts were deposited, the climate was cool. The Port Nelson area lay near the forest-tundra boundary, the Mountain Rapids area lay within the boreal forest, and the Limestone Rapids site lay beyond the treeline. Comparable conditions prevail in those areas today. The cemented, reddened upper horizon in the interglacial gravels along North Knife River may record a warmer, soil-forming phase within the same interglaciation. On the basis of their stratigraphic position, climatic indications, and correlation with the Missinaibi Formation in northern Ontario, these nonglacial deposits are assigned to the Sangamon Interglaciation. "Sangamon" is used here to encompass all the Sangamon Stage. The peat beds may belong to the initial or waning phases of oxygen isotope stage 5e, or to stage 5a. Arguments supporting a 5e interpretation are given in Dredge et al. (1990).

Wisconsin Glaciation

Evidence from northeastern Manitoba indicates that this region was continuously covered by glacial ice during the entire Wisconsin Glaciation, but that the position of the confluence between northern provenance and eastern provenance ice shifted during that time.

Ice flow indicators suggest that the main northern centre of glacial outflow was in the central part of western Keewatin, although this centre gradually shifted to southeastern Keewatin; final flow was radial to an ice remnant lying near Hudson Bay just north of the Manitoba border (Dredge et al., 1986). The colour and clast composition of the tills of eastern provenance indicate much variation in ice trajectory within that ice domain during glaciation. The earliest and main ice flow deposited a grey limestone-dolomite till (Long Spruce till), whereas later ice flow produced a till with a red-brown tinge (Sky Pilot till) containing Devonian mudstones from the south-central part of Hudson Basin. The grey tills are thought to have either Labradorean or Hudson source areas, whereas the upper till may reflect a shift to a Hudson ice divide.

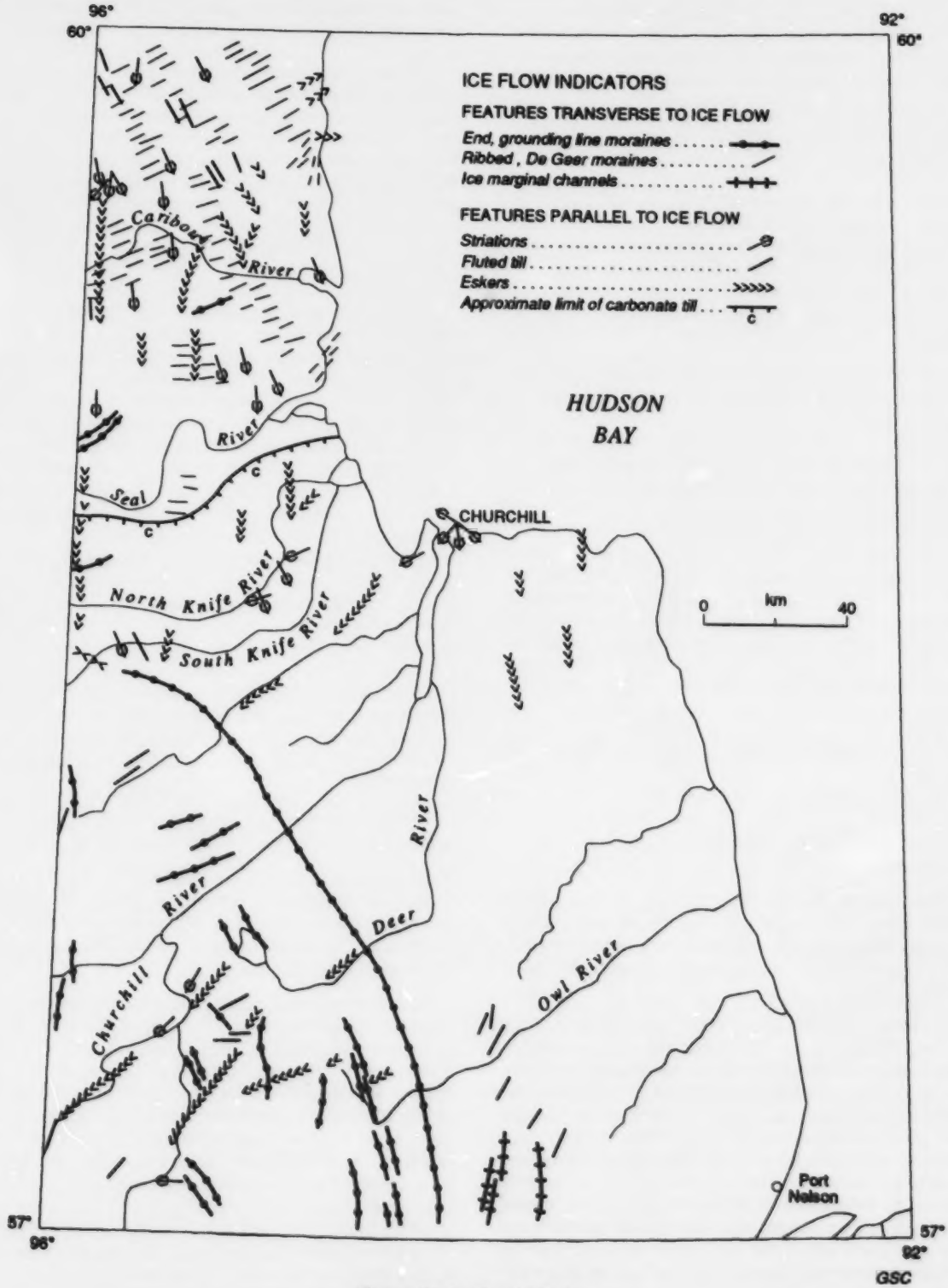


Figure 30. Ice flow indicators.

Near Tadoule Lake in northwestern Manitoba, the lower part of the Wisconsin till sheet contains Paleozoic fossils and abnormally high amounts of matrix carbonate. These data suggest that, during the early part of the last (Wisconsin) glaciation, Labradorean-Hudson ice extended as far west as Chipeweyan Lake (Fig. 31C; Dredge and Nixon, 1982; Dredge, 1988b) in northern Manitoba, and as far as Leaf Rapids farther south (Kaszycki and DiLabio, 1986; Dredge and Cowan, 1989), depositing the Long Spruce till. The same ice reached as far north as the Churchill area, leaving striae oriented at 240°.

During the main Wisconsin Glaciation, the Hudson ice margin subsequently receded to the east, while Keewatin ice advanced (Fig. 31D), and considerable fluctuation of the two ice sheets took place over northeastern Manitoba. The

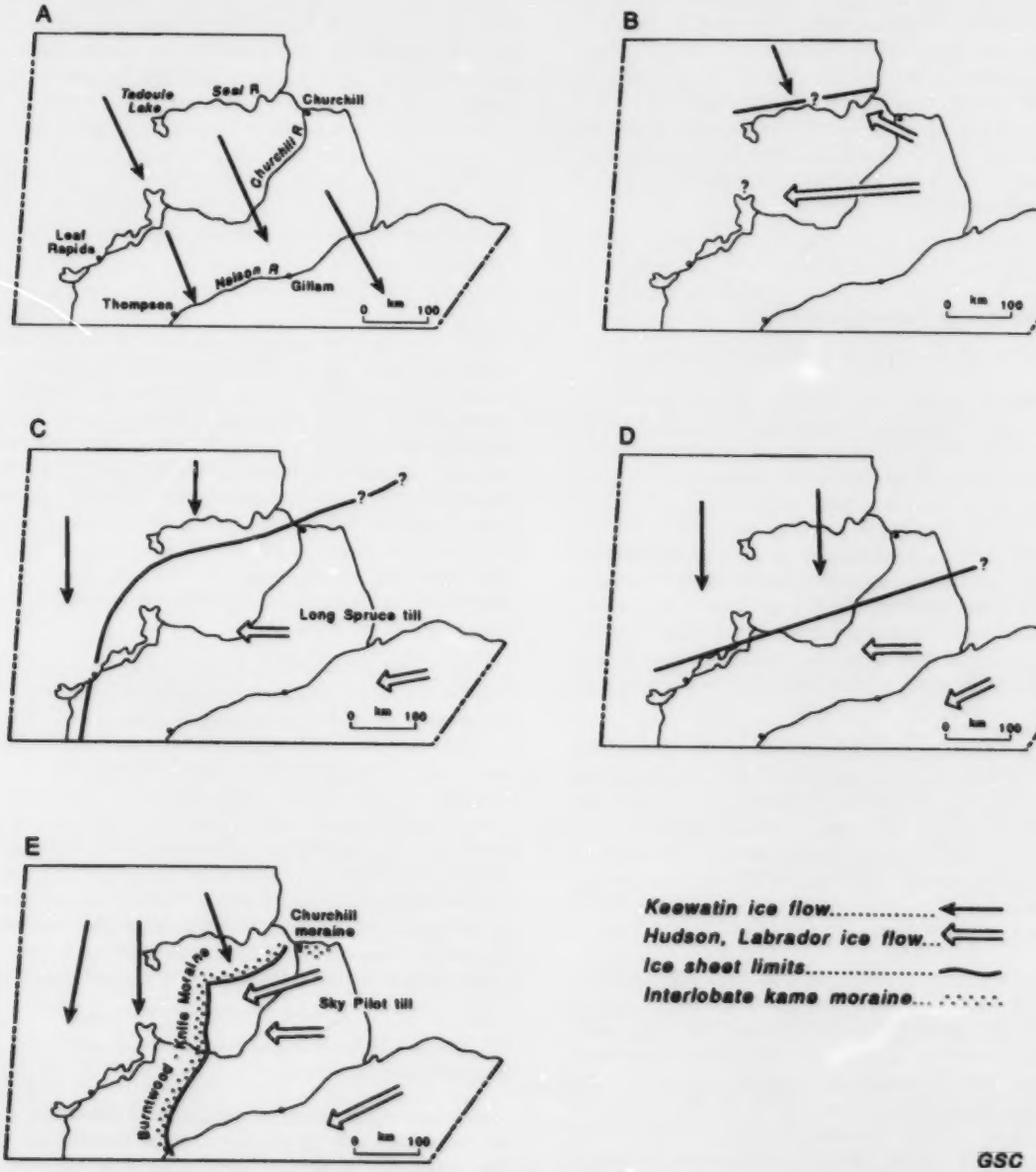


Figure 31. Pre-Wisconsin and Wisconsin glaciations in northern Manitoba. **A.** The earliest recorded glaciation (Keewatin) and **B.** succeeding pre-Wisconsin glaciation (mainly Labradorean?) which deposited the Amery till. Shifting ice flow patterns during **C.** the Early **D.** Middle and **E.** Late Wisconsin glaciation.

abundance of Precambrian clasts in till, and the distribution of east-west oriented moraines in the central part of the study area, indicate that Keewatin ice flowed southwards beyond the Precambrian-Paleozoic contact, overrode older calcareous tills in the Hudson Bay lowlands, and reached at least as far south as Churchill and Little Beaver rivers. Keewatin ice extended eastwards beyond the coast for an unknown, but probably short, distance into the Hudson Basin, where it coalesced with Hudson-Labradorean ice.

The silty texture and high matrix carbonate contents of the surface (Sky Pilot) till, in the southern two-thirds of the map area, indicate that Late Wisconsinan Hudson ice later advanced, extending westwards beyond the Paleozoic- Precambrian contact as far west as (roughly) North Knife Lake (97°W). It probably did not reach as far north as Churchill, where the prevailing ice flow is 180° (Fig. 31E). The zone of convergence of the coterminal Keewatin and Hudson ice masses is marked by interlobate kame and esker gravels.

Deglaciation

Ice recession against Lake Agassiz

Regime of the two ice masses at the time of deglaciation

About the time of deglaciation, the Keewatin and Hudson ice converged along an imaginary line running from about 58°25'N at the western boundary of the map area, east-northeastwards as far as Holcroft Lake. Meltwater flowed from both ice masses towards and along the convergence, depositing a string of interlobate kames. The kame moraine segments developed sequentially at the ice front as the two ice masses separated and retreated. The Burntwood-Etawney moraine in central Manitoba (Klassen, 1983) and the South Knife interlobate kame moraine in this area mark the location of the convergence at the beginning of deglaciation in the map area. The Holcroft Lake kame and Churchill moraine mark slightly later and final interlobate positions.

Although both the Keewatin and Hudson-Labradorean ice masses were active early during the last glaciation, by late glacial time and during deglaciation the Keewatin and Hudson ice masses had markedly different glaciological regimes (Dredge, 1983c). These differences affected the patterns and timing of deglaciation (described in the next section), and allowed the proglacial lake, which abutted the retreating ice fronts, to expand well into the Keewatin domain.

Keewatin ice, with its centre well above the influence of sea and lakes, remained stable and grounded until it finally disappeared. The presence of substratified till, long esker systems, and belts of conjugate ridges indicate an abundance of meltwater, both in subglacial channels and in crevasse systems, suggesting little forward ice flow. The pattern of conjugate ridges (crevasse fillings) and belts of fluted ribbed moraine suggest a regime locally characterized by plastic flow interspersed with thin, brittle ice in which movement occurred by shearing. Ice recession occurred by downwasting, melting of the ice front, sapping of the southern margin by a proglacial lake, and possibly sapping of the eastern margin by the postglacial Tyrrell Sea.

Hudson ice, in contrast, flowed actively and vigorously both during main glacial time and during deglaciation. The pattern of carbonate drift indicates that ice streams were part of the flow regime. The ice was thick enough to remain grounded despite the buoying forces of a deep proglacial lake against its front, and the rising postglacial sea somewhere behind. This situation, however, produced a quasi-stable condition, one of potential instability, resulting in a catastrophic end to the ice sheet (discussed later). Ice flow was plastic enough to produce broad grounding line moraines (as opposed to shear moraines) and to form fluted bedforms even during the last stages. The relatively close spacing of these moraines and evidence of a readvance indicate that forward flow was vigorous enough to prevent rapid backwasting of the ice front despite the calving that occurred where the ice front lay against a deep glacial lake. An ice ramp or ice shelf extended into the proglacial lake, from which icebergs calved and later grounded on submerged moraines. The substratified diamicton associated with the retreat shows the intimate relationship between this ice mass and Lake Agassiz.

General pattern of ice recession

Although continental deglaciation was caused primarily by climatic factors, the rate and pattern of ice retreat in northeastern Manitoba was affected greatly by the development of Lake Agassiz. During deglaciation, natural drainage towards the east was blocked by Hudson ice. A deep proglacial lake therefore developed, expanded as the ice sheets retreated, and persisted as long as Hudson ice remained grounded in Hudson Bay. The presence of this lake accelerated the retreat of the ice fronts by acting as a heat source, and by mechanically sapping the ice margins through buoyancy and wave erosion.

This area provides few marginal indicators from which to draw successive marginal positions of Keewatin ice, but the general picture of ice recession (Fig. 32A-F) has been reconstructed using small end moraines, esker trends and sizes, and cross-cutting striae, together with more abundant data from neighbouring areas (Dredge et al., 1986). The shape and position of successive Hudson ice margins are based on grounding line moraines, submarginal channels, and ice moulded bedforms. The main elements in the pattern are the progressive opening of the suture between two ice margins, the recession and changing configuration of the Keewatin and Hudson ice masses, and the contemporaneous expansion of Lake Agassiz into the areas vacated by the melting ice sheets.

Separation of Keewatin and Hudson ice sheets along the interlobate zone

During the initial stages of deglaciation Keewatin ice still flowed southwards in this area while Hudson ice flowed westwards. The margin of Hudson ice was convex towards the west. Deglaciation in northeastern Manitoba began along the zone of ice convergence, this being the weakest and thinnest part of the ice. Lake Agassiz initially formed as a triangular wedge in this zone and gradually expanded it.

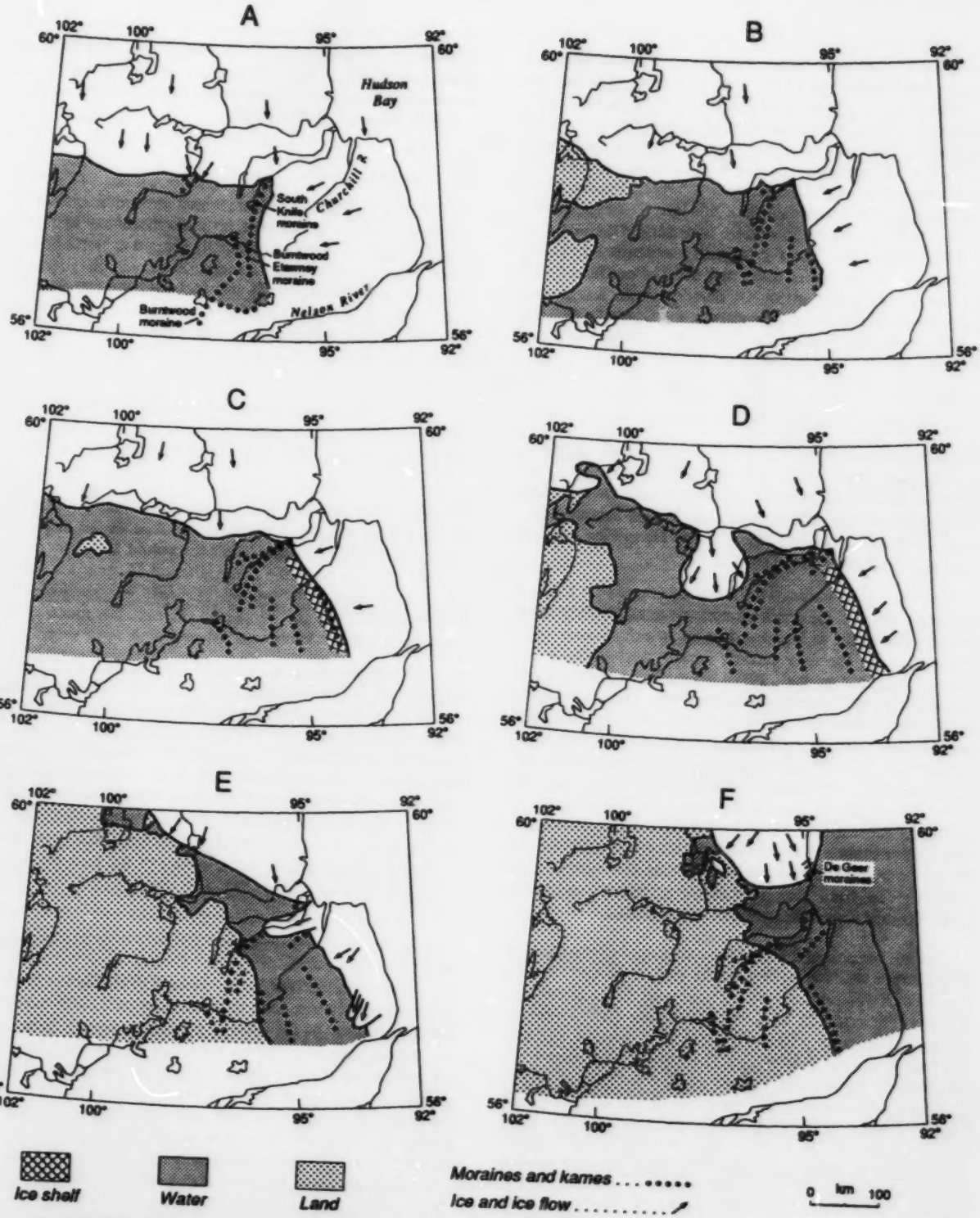


Figure 32. Pattern of ice retreat and expansion of Lake Agassiz. **A.** Calving bay reentrant along the interlobate moraine and preferential expansion of Lake Agassiz into the Keewatin ice domain. Lake level at 442 m. **B.** Development of grounding line moraines. Lake level at 377 m. **C.** Development of a concave grounded Hudson ice front, with an abutting calving ice shelf. Lake level at 380 m. **D.** Quinn Lake readvance. **E.** Surges along the Hudson ice margin and rapid changes of lake level as new outlets open. **F.** Penultimate lower limb of the Keewatin ice divide, isolated glacial lakes, and the Tyrrell Sea.

Where sediment-laden meltwater debouched from tunnels and channels along the zone of convergence into the proglacial lake, mounds of sediment were successively deposited. During the initial opening, south and west of the map area, the path of separation is marked by almost continuous hummocky ridges of sediment, named the Burntwood-Etawney Moraine south of 57°N (Klassen, 1983) and South Knife Moraine north of this line. The easternmost part of this ridge enters the western boundary of the map area at 58°25'N latitude. From this point eastwards successive positions of the ice front along the zone of confluence are marked by a double string of disconnected, low-angled mounds and short esker segments between South Knife River and Holcroft Lake, and by the Churchill moraine.

Retreat of Keewatin ice and development of the Hudson calving bay

Following initial separation of the Keewatin and Hudson ice in this area, deglaciation proceeded by widening of the reentrant along the interlobate zone and by frontal recession. The proglacial lake, which began as a wedge occupying the suture, expanded until its margins lay along two disjunct, separated ice fronts (Fig. 32A).

Keewatin ice continued to flow southwards over much of this area, despite the shift in the centre of outflow from western Keewatin to Yathkyed Lake, which caused major changes in the ice flow pattern farther west (Dredge and Nixon, 1982; Dredge et al., 1986). As the Keewatin ice divide migrated towards northeastern Manitoba, the ice mass in northeastern Manitoba thinned and lost vigour. With backwasting of the ice front against Lake Agassiz exceeding forward flow of ice, the Keewatin ice underwent a fairly rapid net retreat. The configuration of the ice front was controlled by local topography. During the early part of this phase the Keewatin ice margin trended east-west, perpendicular to topographic contours. By the end of this phase the west part of the ice margin had receded more than the east, and the resulting ice front was reoriented northwest-southeast. Sedimentation from this ice sheet was minimal.

During recession, the Hudson ice margin changed shape from convex westwards, beyond the area, to straight, when it lay at the western margin of the map area. It became increasingly concave as a major calving bay developed against the deepening lake (Fig. 32B, C). Hudson ice flowed westwards during this stage. The shapes and successive positions of the ice margins are marked by grounding line moraines, which form broad swells in the landscape. An ice ramp or ice shelf protruded beyond the grounding line, from which icebergs calved. The keels of these bergs dragged across older, recently submerged moraines and scarred their surfaces (Fig. 20).

Hudson ice retreated eastwards, parallel to the contours of the land. Thus, the receding ice front abutted against increasingly deepening water. Towards the end of this stage (Fig. 32D), the Hudson ice margin had receded over the local drainage divide (Owl River watershed) into the coastal area of the lowland later subject to the influence of the Tyrrell Sea. The last known position of the ice margin was marked by the interlobate kame at Holcroft Lake in the north, and by the north-south trending submarginal drainage channels north of the Weir River (57°N;93°35'W).

Lake Agassiz episode

The proglacial, high level lake, which expanded against the receding ice fronts in this area, is the northernmost extremity of Lake Agassiz. This lake originally formed in North Dakota when the ice sheets began to recede about 11 700 years ago (Clayton and Moran, 1982) and followed the receding ice margins north. The lake's configuration changed as it evolved (Dredge, 1983c), in harmony with the opening of successive new outlets and with isostatic rebound of the southern part of the lake basin.

This section sums up several aspects of Lake Agassiz. More detailed accounts, especially on waterplanes, have been reported previously (Dredge, 1983c; Dredge et al., 1986).

Configuration and limits of the northern lake basin. The configuration of Lake Agassiz in this area varied as the ice margin retreated and water levels fluctuated. Its northern and eastern margins were the Keewatin and Hudson ice fronts. Because of regional topography, the lake was shallowest to the west and north and deepest in the east. For much of the lake's existence its basin was covered with deep water.

The distribution of surface and buried postglacial lacustrine deposits indicates that the lake extended northwards somewhat beyond North Knife River, but that it did not reach Seal River. The eastern boundary of the lake is presently unknown, but lacustrine deposits underlie till and marine sediments at least as far east as Lofthouse Lake, and farther south, possibly as far east as the mouth of Nelson River. Fine textured sediment also covers the Kaskattama Highland in extreme northeastern Manitoba, and thus Lake Agassiz may have extended into part of the area presently occupied by Hudson Bay (Fig. 33).

Sedimentation. The main sediment supply in the northern part of the lake came from nearby ice masses. Most sediment in this study area derives from Hudson drift. Sedimentation occurred mainly in a deep water environment, with material being deposited at the glacier grounding line or from the protruding ice ramp. Brown, silty, calcareous, waterlaid till was deposited near the grounding line and in places, graded deposits of flow till sloughed off the glacier surface. Material debouching from subglacial conduits (esker channels) produced additional turbidites consisting of turbid units, crossbeds, graded and plane beds, varves, and massive facies. Varved clays were deposited regionally near the ice front. The thinning upwards sequence of at least 150 varves on North Knife River indicates a steadily retreating ice front against a lake that lasted at least 150 years in that area. A shorter sequence of varves at Port Nelson may relate to a smaller, shorter-lived lake there (Lake Netterville of Dredge and Grant, 1982). Fine silt, carried in suspension by currents, was deposited beyond the ice ramp and, in places, beyond

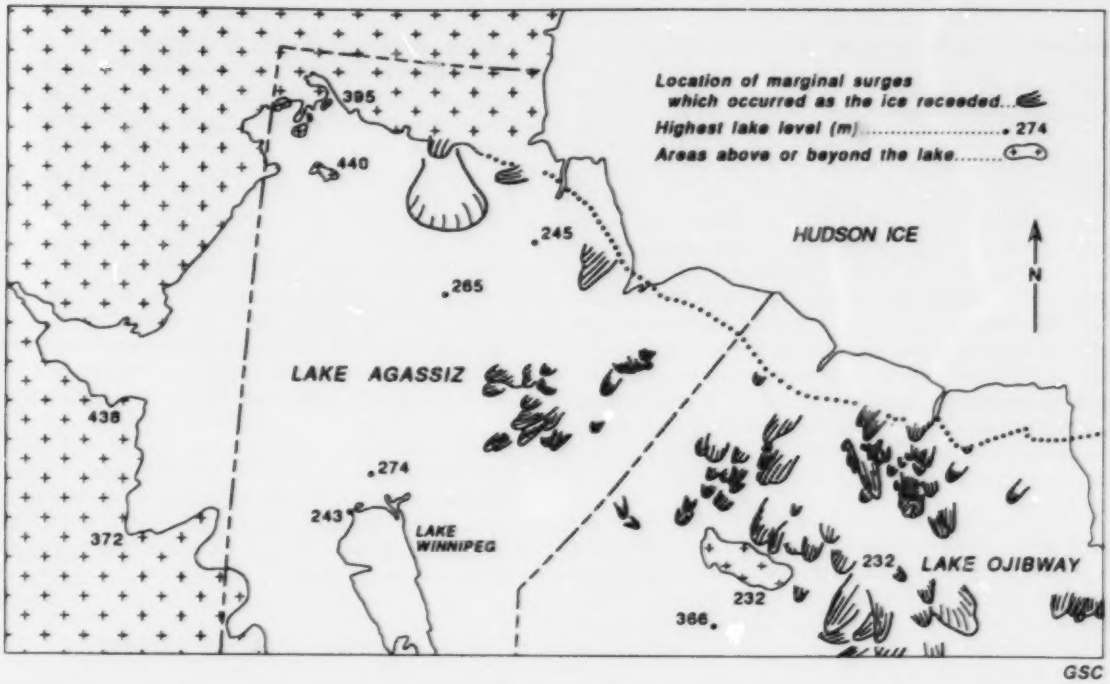


Figure 33. Area covered by Lake Agassiz in northern Manitoba and adjacent areas.

(westwards of) the Late Wisconsinan limit of Hudson ice cover (Dredge et al., 1986; Kaszycki and DiLabio, 1986). These deposits formed a blanket over the till and proximal varves as the ice front receded. Bergs drifting from the calving ice front have inscribed criss-crossing patterns into these deposits where they grounded on underwater ridges (Fig. 20; Dredge, 1982a).

In most places, deepwater deposits are the uppermost sedimentary unit in the lacustrine sequence. Beaches are absent because the lake stood well above the highest land for most of its duration. The general absence of littoral cover deposits and regressional beach sequences suggests rapid drops in lake level associated with the uncovering of new outlets along the retreating Hudson ice margin.

Main levels and lake stages. When Lake Agassiz first incurred as a thin wedge along the zone of Hudson-Keewatin convergence, the elevation of the lake stood at 442 m (Dredge, 1983c), about 200 m above the highest land in northeastern Manitoba. Lake levels dropped following this high stage. The lake surface fell first to 425 m and then to 410 m as the lake expanded. When the lake was at these elevations it emptied into the Nipigon system through an outlet south of the Hudwin moraine in Manitoba and the Agutua moraine in northwestern Ontario.

By the time the ice had receded to a position east of Owl River Highlands and the lake had reached its maximum expansion, the water surface stood at about 380 m (1250'), still 135 m above the highest land. Part of the Keewatin ice margin west of this area then readvanced into the lake (Quinn Lake Readvance, Fig. 32D). During this stage Lake Agassiz drained eastwards into Lake Ojibway through the lowland directly south of Kaskattama Highland.

Subsequently, as the Kaskattama outlet eroded or new outlets opened, the lake contracted and water levels fell. An esker delta at 210 m and the wave cut notches at 245, 210, 180, 155, and 136 m in the area of the Owl River drainage divide mark temporary periods of water level stabilization.

Age. The ages of the various lake phases in this area are imprecisely known, but the major lake episode can be bracketed. The earliest phase in northeastern Manitoba must postdate the Grand Rapids phase, because the ice front then lay about 350 km south of our study area. Klassen (1983) reported a date of 8800 BP for the Grand Rapids phase, although Ringrose (1975) suggested a date closer to 8300 BP (GSC-1679). Freshwater shells in alluvium along Churchill River yielded a date of 7760 ± 370 BP (GSC-3348) (Nielsen and Kroker, 1982) and indicate that the lake had drained by about that time. The final lake phase must slightly predate the marine episode for which there is a date of 7750 ± 140 BP (GSC-3070) on marine shells overlying surge till and lacustrine sediment on North Knife River. Together these two dates suggest that the Lake Agassiz episode ended about, but prior to, 7800 years ago.

Readvance and catastrophic demise of Hudson ice

Just before Lake Agassiz ceased to exist, parts of the southwest-flowing Hudson ice front readvanced into the lake. The reorientation of north-south moraines into southwest-trending drumlinoid forms records this shift in the area between O'Day and Silcox (located on the CN railway). Another readvance extended at least 20 km into the lake, deformed (contorted and broke) varved clays along North Knife River, and emplaced a thin till over the lake sediments (Fig. 32E). The advance occurred just prior to 7750 ± 140 BP (GSC-3070), which represents the age of shells in marine deposits overlying the till. The style, limited areal extent, and timing of the readvances in this area suggest that the readvances are marginal surges of the ice front, equivalent to the Cochrane readvances of northwestern Ontario. Grounded components produced drumlinoidal bedforms, whereas floating components left only iceberg scour marks.

There is no evidence of the Hudson ice sheet following the readvances. Possibly these readvances, and others like them beyond the study region, were the critical contributing factors that caused the catastrophic break-up and sudden disappearance of ice in Hudson Bay. Break-up would have occurred once the buoyant forces acting on Hudson ice exceeded the static ice load.

The buoying forces acting on the ice margin were first the proglacial lakes, Lake Agassiz and Lake Ojibway, which deepened as the ice receded down the contours of the land, and affected the entire southern sector of the ice front; secondly, the rising Tyrrell Sea, which may have been flooding into the northern part of the Hudson domain during the last stages; thirdly, the considerable quantities of meltwater, which may have been lying within the ice, particularly at its base.

The static load was decreased during deglaciation by glacial surges along the ice perimeter, which flattened the profile, and by the general ablation and downwasting at the upper surface of the ice.

Calving of the Hudson ice front in this area and along much of the perimeter may have oversteepened long sections of the ice mass, which was perhaps already destabilized by rising sea levels. The ice responded by surging in various places along its southern perimeter. This action thinned and flattened the profile of Hudson ice and may eventually have caused uncoupling of the glacier from its bed and total break-up of the ice sheet in Hudson Bay. The Hudson domain would thus have rapidly evolved into a large ice pan. This catastrophic event, by removing the ice barrier that had upheld the proglacial lakes, marked the end of glacial Lake Agassiz and the beginning of the Tyrrell Sea episode.

Recession of Keewatin ice to a final centre near Hudson Bay

After the break-up of Hudson ice and draining of Lake Agassiz the land-based Keewatin ice gradually receded to final remnant centres of outflow (Fig. 32F). Esker trends and crosscutting striae show the pattern of contraction of the ice margin and indicate that late flow in the field area was radial to a small remnant centred at about 96°W, and lying directly north of the Manitoba border. Flow in the west remained southwards, but southeasterly flow dominated the coastal part of this area.

The abundance of eskers, ribbed moraine, and crevasse fillings suggest that the thinning ice was water-laden. Small De Geer moraines lying close to the coast of Hudson Bay may mark recessional ice margin positions and indicate an ice mass in contact with Tyrrell Sea, which could have inundated part of the decaying ice sheet. The incursion of Tyrrell Sea into this area while part of the Keewatin ice sheet was still extant explains the absence of marine deposits over till even at low elevations in the northernmost part of the region.

Because meltwater was free to drain southwards along natural gradients, no glacial lakes developed in front of the Keewatin ice sheet in northeastern Manitoba during its final recessional stages; however, isolated glacial lakes did develop on the western flank of this ice remnant in adjacent areas to the west (Dredge et al., 1986).

Tyrrell Sea episode and postglacial sea level changes

The Tyrrell Sea, a name proposed by Lee (1960), was the body of water in the Hudson Bay lowlands that reached levels higher than present owing to glacioisostatic deformation. It began as a high sea and regressed to the present position of Hudson Bay. The Tyrrell Sea flooded the central and southern parts of the map area directly following break-up of Hudson ice, while Keewatin ice remnants still lay in the northern region.

Configuration and maximum extent

Figure 34 shows the area covered by the Tyrrell Sea, elevations for the marine limit, and locations of radiocarbon dated material used in the construction of emergence curves and in the interpretation of glacial history. Radiocarbon ages are shown in Table 2. The marine limit was determined by the elevation of the highest beaches and wave-cut marine notches. More precise limits are difficult to determine because of the extensive peat cover that masks deposits and small relief features.

North of Weir River (57°N; 93°35′W), the postglacial sea extended about 200 km inland from the present coast and had a coastline roughly parallel to the present coast. South of Weir River the sea extended as much as 250 km inland and possessed a coastline with a configuration much more intricate than the present shore. Nelson, Stupart, and Gods rivers formed broad reentrants, and the uplands south of Kaskattama River stood offshore as large islands.

The elevation of the marine limit is lowest near Nelson River (120 m) and rises both to the north and to the south. Southeast of Nelson River it rises to about 145 m. Between Weir and South Knife rivers the marine limit lies just above the Great Beach. The limit rises gradually from 130 m to about 145 m over a distance of 180 km, giving a rise of 0.08 m/km in a north-northwesterly direction. North of South

Knife River, the elevation of the marine limit rises abruptly. The marine limit lies at 165 m on an esker 33 km north of the South Knife kame moraine and rises to more than 180 m over a distance of 45 km. The gradient for this stretch is thus 0.3 m/km in a northerly direction. North of the 180 m limit (north of Seal River) there is little evidence of marine washing above about 150 m elevation. The differences in elevation and gradient of the marine limit north and south of the interlobate moraine reflect contrasting ice loads and glacial histories of the Keewatin and Hudson ice sheets. The abrupt change in marine limit near South Knife River occurs at the zone of confluence of the two ice sheets. The regional distribution of marine limit elevations within the Hudson ice regime together with radiocarbon dates suggest that the loading centre lay in a direction northeast of Port Nelson. The relatively low amount of emergence in areas under Hudson ice relative to those under Keewatin ice indicates either that substantial isostatic rebound occurred prior to the Tyrrell Sea episode,

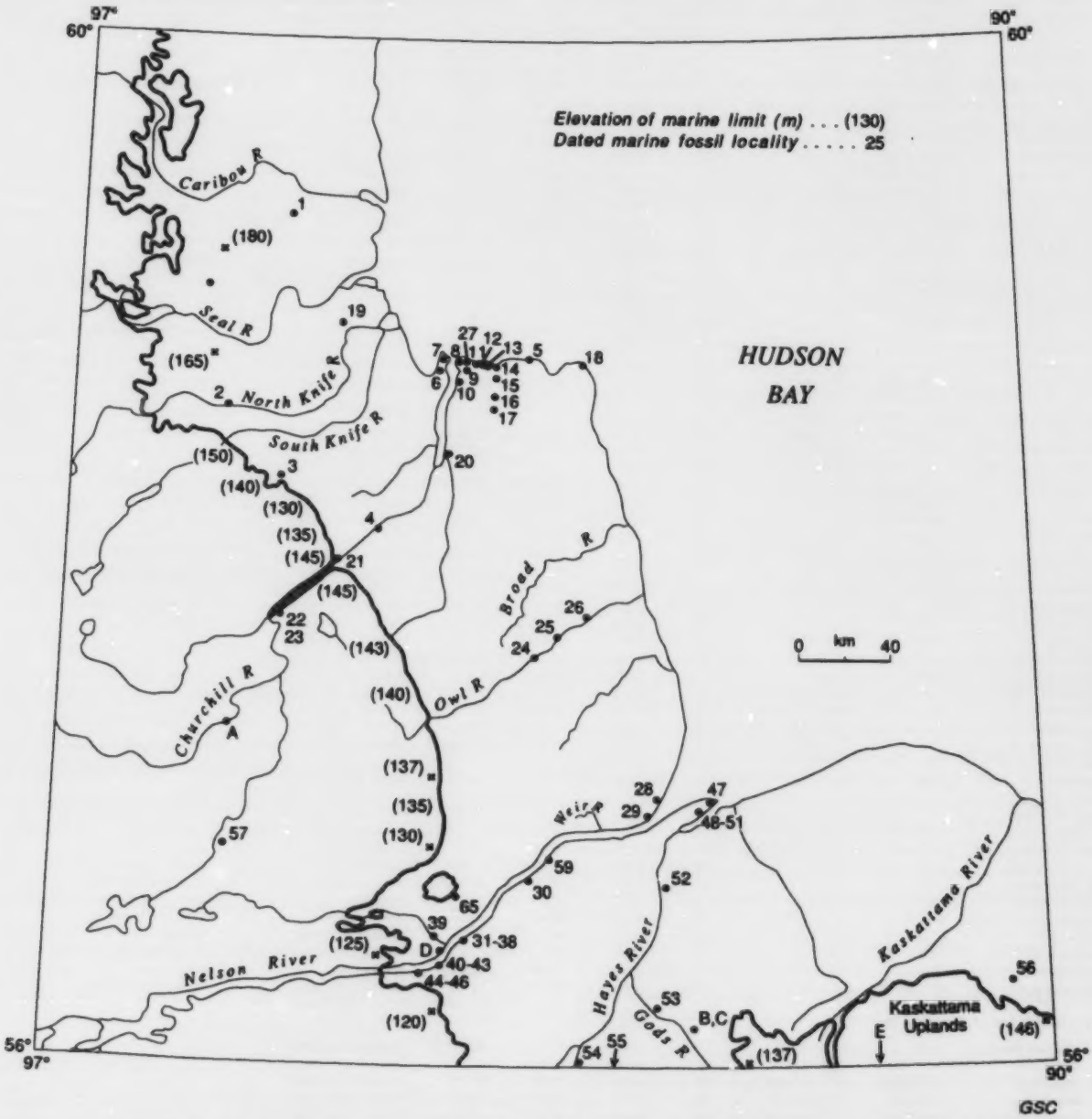


Figure 34. Areas inundated by the Tyrrell Sea. Bracketed numbers show the elevation of the marine limit in metres; other numbers denote dated marine fossil localities; letters indicate Sangamon deposits included in the radiocarbon date list (Table 2).

Table 2. Radiocarbon dates (localities are shown on Figure 34)

Site	Age (years BP)	Lab No.	Elevation (m)	Material	Latitude/Longitude		Reference	Comments
Churchill area								
1. Caribou River	6790 ± 100	GSC-2579	90	shells	58°19'	95°23'	Blake, 1982	deltaic
2. N. Knife River	7770 ± 140	GSC-3070	110	shells	58°33'	95°50'	Blake, 1982	from sands, early emergence
3. Gt. Beach	7270 ± 120	GSC-92	142	shells	58°11'	95°03'	Craig, 1969	elev. may be 110 m
4. Churchill River	8010 ± 95	GX-1063	67	shells	58°06'	94°42'	Wagner, 1967	location approximate
5. Watson Pt.	385 ± 80	GX-1073	4	shells	58°45'	93°21'	Wagner, 1967	location approximate
6. Churchill	3190 ± 80	GX-1065	38	shells	59°45'	94°16.5'	Wagner, 1967	location approximate
7. Seahorse	3580 ± 105	S-736	35	shells	58°45'	94°15'	Rutherford et al., 1975	
8. Churchill	3080 ± 130	GSC-245	5	peat	58°45.2'	94°06'	Lowdon et al., 1971	
9. Churchill	3040 ± 130	GSC-261	23	shells	58°44.5'	94°04.8'	Lowdon et al., 1971	from littoral sand
10.Goose Ck.	3430 ± 140	GSC-735	5	shells	58°40.3'	94°10.2'	Craig, 1969	in stony clay
11.Churchill	5020 ± 140	GSC-1549	22	shells	58°44.4'	94°04.6'	Craig, 1969	
12.Rocket range	2120 ± 130	GSC-723	22	shells	58°45.4'	93°58.8'	Craig, 1969	littoral sands
13.Rocket range	1020 ± 140	GSC-684	7	shells	58°45.6'	93°57.0'	Craig, 1969	littoral gravel
14.Rocket range	1240 ± 130	GSC-682	11	shells	58°44.8'	93°50.4'	Craig, 1969	littoral gravel
15.Twin Lakes	2320 ± 130	GSC-683	27	shells	58°42.2	93°50.6'	Craig, 1969	littoral gravel
16.Twin Lakes	3180 ± 140	GSC-685	39	shells	58°37.1'	93°48.7'	Craig, 1960	gravel
17.Twin Lakes	3190 ± 80	GX-1072	30	shells	58°36.4'	93°49.4'	Wagner, 1967	location approximate
18.Cape Churchill	0 ± 130	GSC-1226	0	shells	58°45'	93°12'	Lowdon et al., 1971	intertidal
19.N. Knife R.	4000 ± 90	GSC-3851	30	shells	58°53.5'	94°58.0'	Blake, 1988	in silty clay
20.Deer River	5150 ± 110	BGS-796	30	shells	58°23.4'	94°14.2'	Nielsen, unpub.	
21.Churchill R.	3530 ± 100	BGS-793	100	wood	57°58'	95°00'	Nielsen, unpub.	
22.Churchill R.	7670 ± 370	GSC-3348	134	shells	57°40'	95°25'	Blake, 1982	freshwater shells
23.Churchill R.	5980 ± 100	BGS-980	134	wood	57°40'	95°25'	Nielsen and Dredge, unpub.	basal peat, log
24.Owl River	6880 ± 130	GSC-3855	59	shells	57°36'	93°32'	Blake, 1988	
25.Owl River	5310 ± 80	GSC-3856	49	shells	57°41.5'	93°21.5'	Blake, 1988	
26.Owl River	5290 ± 70	GSC-3896	37	shells	57°46.3'	93°11'	Blake, 1988	sand below marine diamicton
27.Churchill	2360 ± 100	GSC-4507	7	shells	58°45.1'	94°8.6'	Dredge and Nielsen, unpub.	
57. Recluse Lake	6490 ± 170	GSC-1738	185	peat	56°52'	95°47'	Lowdon et al., 1977	basal peat
58. Spruce Lake	4850 ± 60	GSC-2567	210	wood	59°05'	96°45'	Lowdon and Blake, 1978	basal peat
Nelson River area								basal peat
65.Charlebois	6280 ± 80	GSC-2760	100	peat	56°40'	95°05'	Roggensack, unpub.	
28.Port Nelson	7020 ± 100	GSC-3921	16	shells	57°1.6'	92°38.0'	Blake, 1988	
29.Flamborough Hd.	7370 ± 90	GSC-3930	30	shells	56°58.1'	92°47.0'	Blake, 1988	
30.Angling R.	7250 ± 80	GSC-3904	35	shells	56°45.0'	93°36.5'	Blake, 1988	surface at 35 m
31.Sundance	7180 ± 70	GSC-3326	76	shells	56°32.0'	94°05'	Nielsen and Dredge, 1982	re-collection of BGS 714
32.Sundance	6900 ± 150	BGS-714	76	shells	56°32.0'	94°05'	Nielsen and Dredge, 1982	
33.Sundance	6900 ± 100	BGS-798	76	shells	56°32.0'	94°05'	Nielsen and Dredge, 1982	
34.Sundance	7030 ± 170	GSC-2294	90	shells	56°32.0'	94°05'	Klassen, 1985	
35.Nelson Rt. bk	6760 ± 80	GSC-3367	67	shells	56°32.5'	94°06'	Nielsen and Dredge, 1982	re-collection of BGS 791
36.Nelson Rt. bk	6760 ± 100	BGS-791	67	shells	56°32.5'	94°00'	Nielsen and Dredge, 1982	
37.Nelson Rt. bk	6280 ± 160	BGS-711	67	shells	56°32.5'	94°00'	Nielsen and Dredge, 1982	re-collection of BGS 791
38.Nelson Rt. bk	6500 ± 140	BGS-797	67	shells	56°32.5'	94°00'	Nielsen and Dredge, 1982	upper sand unit
39.5-mile hole	7120 ± 120	BGS-906	84	shells	56°31.7'	94°15'	Nielsen, unpub.	
40.Nelson L. bk (418)	6990 ± 130	BGS-712	82	shells	56°25.8'	94°12'	Nielsen and Dredge, 1982	
41.Nelson L. bk	7050 ± 150	BGS-815	90	shells	56°26.1'	94°10.5'	Nielsen, unpub.	
42.Nelson L. bk	6750 ± 150	BGS-713	90	shells	56°25.2'	94°13'	Nielsen and Dredge, 1982	
43.Nelson L. bk	7300 ± 200	BGS-814	90	shells	56°25.0'	94°14'	Nielsen, unpub.	
44.Long Spruce	8000 ± 200	BGS-812	105	shells	56°24.9'	94°20.2'	Nielsen, unpub.	
45.Long Spruce	7760 ± 80	GSC-3916	100	shells	56°24.9'	94°20.2'	Nielsen and Dredge, 1982	re-collection of BGS 812
46.Nelson R.	8200 ± 300	BGS-813	90	shells			Nielsen, unpub.	
59.Island	6900 ± 130	GSC-3928	15	shells	56°50'	93°30'	Blake, 1988	
Hayes River area								
47.York Factory	660 ± 190	GSC-1468	2	wood	57°03'	92°14'	Simpson, 1972	
48.York Factory	1930 ± 130	GSC-1305	5	wood	56°59'	93°39'	Simpson, 1972	
49.York Factory	2065 ± 125	GX-2061	9	wood	57°00'	92°15'	Simpson, 1972	location approximate
50.York Factory	1055 ± 125	GX-2062	4	wood	57°00'	92°15'	Simpson, 1972	location approximate
51.York Factory	1250 ± 105	GX-2063	2.3	wood	57°00'	92°15'	Simpson, 1972	location approximate
52.Hayes R.	4880 ± 140	GSC-1745	21	wood	56°48'	92°42'	Klassen and Netterville, 1973	in alluvial deltaic sand
53.Gods R.	6610 ± 100	GSC-1955	75	shells	56°15'	92°45'	Lowdon et al., 1977	in sand
54.Hayes R.	7570 ± 140	GSC-678	115	shells	56°2.3'	93°17'	Lowdon and Blake, 1970	in silty clay, marine limit at 130 m
55.Stupart R.	7110 ± 90	GSC-3926	90	shells	55°59'	93°23'	Blake, 1988	upper sand
56.Kaskattama	8530 ± 220	GSC-896	125	shells	56°16'	90°24'	Lowdon and Blake, 1970	marine limit at 140 m
Dates Pertaining to pre-Holocene time								
A. Mountain Rapids	>32 000	GSC-3074	170	wood	57°19'	95°47'	Dredge et al., 1990	
B. Gods River	>41 000	GSC-1736	43	wood	56°09'	92°31'	Netterville, 1974	
C. Gods River	>49 000	GSC-4471 HP	80	wood	55°52'	91°15'	Dredge et al., 1990	
D. Nelson River	>49 000	GSC-4420 HP	90	wood	56°29'	94°07'	Dredge et al., 1990	
E. Echoing River	>51 000	GSC-4444 HP	120	wood	55°55.1'	91°15.0'	Dredge et al., 1990	

Source: - based on Dredge and Cowan, 1989. Site locations are shown on Figure 34.

when the area was deglaciated but occupied by Lake Agassiz, or that the initial Hudson ice load was less. Regional emergence data from other parts of the Hudson ice domain support the first hypothesis. The absence of high level beaches in the extreme northern part of the study area suggests that the sea abutted the thinning Keewatin ice mass, leaving no littoral record of the earliest phases of crustal rebound. De Geer moraines in this area confirm that the Keewatin ice was in contact with deep water. Because Keewatin ice shrank back in contact with the Tyrrell Sea, the maximum elevation of marine effects is variable and time transgressive.

Age of marine transgression

The oldest date on marine shells (7770 ± 140 BP; GSC-3070) in this area (site 2) comes from a pocket of paired valves of *Hiatella arctica* lying at the base of silty marine deposits which directly overlie till deposited during the penultimate Hudson surges. Although the shells lie well below marine limit, they provide an approximate age for the beginning of the marine event in areas formerly occupied by Hudson ice. The shells predate the surface shells along the Great Beach at 140 m (or 125 m according to the NTS sheet), which were dated at 7270 ± 120 BP (Table 2; GSC-92; Craig, 1969). The oldest dates on marine fossils along Nelson River are 7760 ± 80 BP (GSC-3916) and 8000 ± 200 BP (BGS-812) from the lower part of a thick marine sequence near Long Spruce Dam. These dates correspond well with early Tyrrell Sea dates of 7875 ± 200 BP (GSC-14) and 7760 ± 160 BP (GSC-897) in southern Hudson and James bays. Together they confirm the concept of a synchronous marine invasion of the Hudson Bay lowlands. One date of 8010 ± 95 BP (GX-1063; Wagner, 1967) has been reported from Churchill River, but no further documentation on the collection is available. One marine shell date as old as 8500 ± 220 BP (GSC-896) has been reported from the Great Beach at Kaskattama River. It is believed that this date resulted from a mix of ancient and postglacial shells. Individual valves in a similar situation from the Great Beach north of Gillam have been AMS dated. The worn valves gave ages of 39 000 BP (TO-221), which is considered to be nonfinite, whereas the fresh looking valves in the same collection dated 6980 ± 60 BP (TO-220).

In contrast to events in the area of the former Hudson ice domain, elevations on the marine limit and scattered dates relating to the Keewatin ice domain, both in Manitoba (this report) and Keewatin (Lee, 1959), indicate an ice mass that downwasted and backwasted in contact with the Tyrrell Sea. The age and elevation of the highest marine deposits associated with this ice regime vary greatly over short distances. The oldest date from northeastern Manitoba is 6790 ± 100 BP (GSC-2579) from Caribou River (loc. 1).

Sea level changes

Figure 35 shows emergence curves for the Churchill and Nelson-Hayes areas. Curves for other parts of the Hudson Bay region have also been included for comparison. The curve for the Churchill area was constructed from dates on *Mytilus edulis* and a variety of other species found in beach deposits. *M. edulis* are considered to be good indicators of sea level position. The lower part of the Nelson River curve was constructed from detrital wood in alluvium, whereas the upper part is based on marine shells, mainly *Macoma calcarea* and *Hiatella arctica*. Although in many cases the shells can be related to marine waterplanes by interpreting their depositional environment, the graphs actually show minimum emergence. Emergence has been represented by simple, smoothed curves, although the actual pattern of emergence may in fact have been more complex.

Despite inherent inadequacies of the data, the emergence curves point out several interesting ideas about glacial isostacy. First, the oldest dates from the south and west parts of the Hudson Bay lowlands suggest that all areas were inundated at about the same time. Secondly, the curves for the Churchill, Nelson, and James areas lack the initial rapid emergence typical of most emergence curves; the rate of early emergence in northeastern Manitoba is in the order of 30 m per 1000 years, whereas more typical rates are greater than 60 m per 1000 years (B.R. Pelletier, sea level map, personal communication, 1988). Marine limits are also lower than for other parts of the central areas of the Laurentide Ice sheet. Both aspects suggest that substantial restrained rebound occurred beneath Lake Agassiz, during and after deglaciation but before the marine incursion. The lower marine limits alone might only have indicated that this area was farther from early loading centres. Thirdly, emergence in the lowlands is expressed as a "flattened" curve rather than a simple exponential curve. This form probably reflects unloading influence by multiple ice centres, whose deglaciation histories were not in phase. Fourthly, the central Keewatin, Churchill, and Nelson-Hayes curves form a nested set, reflecting loading differences outward from the Keewatin ice centre. Similarly, the Henrietta Maria, James, and Nelson-Hayes curves form a nested set outwards from the Labradorean-Hudson centres. The Nelson-Hayes area, which experienced the least rebound, was farthest away from major ice divides and from subsequent loading areas. Fifthly, the fact that some sets of curves cross others suggests that centres of rebound shifted during the mid-Holocene. Both the general positions of the curves and tide gauge records indicate that Cape Henrietta Maria has the highest present rate of emergence; Churchill has the second highest rate. Although glacioisostacy may be the dominant component of emergence, hydroisostatic effects cannot be ignored. As the land emerges in response to removal of the former ice load, the water load in Hudson Bay is also lessened. Emergence rates therefore exceed those expected from calculations based solely on glacial unloading. Lastly, a plot of known interglacial terrestrial and marine deposits (Dredge and Cowan, 1989) indicates that Tyrrell Sea occupied much the same area and reached the same level as the last interglacial Bell Sea.

Recent sea level changes at Churchill

There is a great disparity in the rates of present emergence reported for the Churchill area. The various figures were calculated by different methods and on different substrates. Calculations determined from bedrock areas, based on tide

gauge records (Barnett, 1970), on shells from raised beach berms on bedrock (this report), and on the elevation of mooring ringbolts near Fort Churchill emplaced by Hearne in 1758 (Tyrrell, 1898a) give rates of about 40 cm per century. The rate determined by geodetic relevelling at Cape Merry would extrapolate to be about 82 cm per century. In contrast to these bedrock sites, rates determined from tundra sites lying on fine-grained unconsolidated substrates are much higher. A rate of 145 cm per century was measured in Beech Bay in the Churchill estuary, and a rate of 219 cm per century was calculated for the same area based on the Robson maps dating back to 1749 (Hansell et al., 1983). Hansell et al. (1983) and Dyke (1988) attribute this extra 1 to 1.5 m of emergence to the development of permafrost and growth of ground ice in saturated recently emerged areas.

Sedimentation, beach ridge development, and coastal changes

Over much of the area the marine record consists of a coarsening upwards offlap sequence of deposits, indicating a regressive sea. Exceptions are found along parts of the lower Nelson River and one section along Owl River, where basal sand units may represent an early transgression. The more

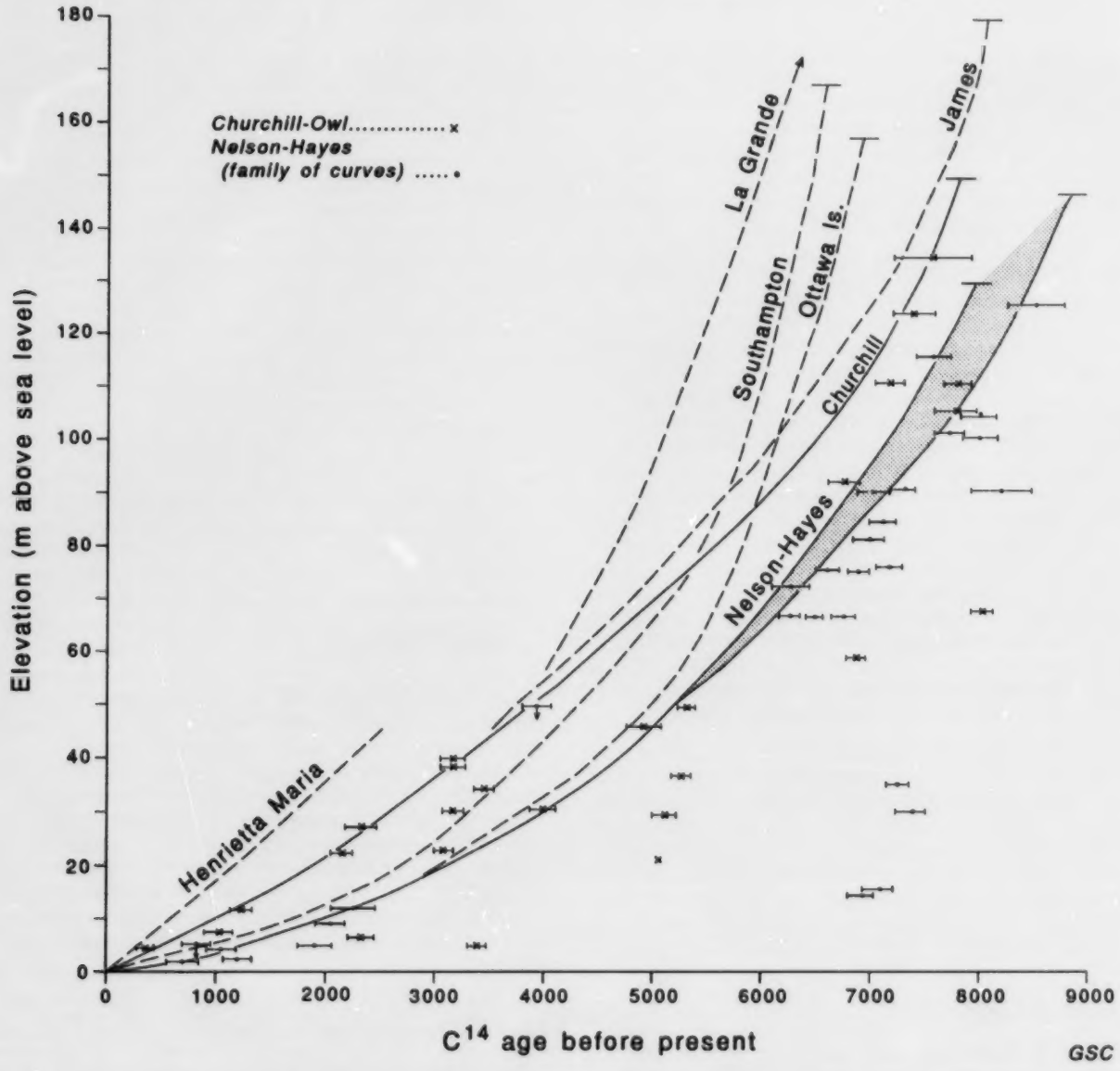


Figure 35. Emergence curves for northeastern Manitoba and other parts of Hudson Bay.

common record consists of poorly compacted glaciomarine deposits containing abundant crushed shells grading to, and overlain by, marine clays. These in turn are capped by littoral sand and tidal silt, thickening seawards, but commonly less than 2 m thick. Abundant ice rafted boulders suggest that sea ice was present from the beginning of the Tyrrell Sea episode up to modern times. The shallowness of the marine sequence, in marked contrast to other areas of the country where sediment-laden glacial meltwaters debouched into high level seas, is the result of the glacial heritage of the Hudson Bay lowland, where the marine-based ice sheet disintegrated rapidly, and where sediment was carried from a deglaciated landmass by rivers into Tyrrell Sea.

There was very little beach ridge development during the early stages of emergence. An exception is the Great Beach (Fig. 8), which begins at the South Knife kame moraine and arcs across the southern part of the map area. It is 200 to 800 m wide and consists of multiple beach ridges and spits. The existence of this feature is problematical, particularly because it can be traced from the interlobate moraine in this area, across northeastern Manitoba and northwestern Ontario as far as Winisk River (Dredge and Cowan, 1989). Although the surface aspect is that of a massive beach, the feature is till cored in some places. Furthermore, this voluminous sandy deposit has developed in a region where the parent material is silty till. Although some material could have been transported and redeposited by rivers and longshore currents, such a source is inadequate to account for the extent and size of the feature. It may therefore be a former interlobate moraine or deglacial grounding line moraine that has been reworked by Tyrrell Sea. In northeastern Manitoba, the major period of berm construction ceased when sea level stood 120 m above present: that is, about 7000 years ago. This change in shoreline regime may be related either to climatic cooling and sea ice between 7000 and about 4500 BP (when berm development resumed), or to topographic factors. If Hudson Bay were iced over, then neither storm waves nor storm berms would develop. Similarly, the icing over of rivers emptying into Hudson Bay would reduce the amount of berm forming sediment. As for topography, the slope of the land is so gentle in this part of the Hudson Bay lowland that except for old morainal rises, waves may not be able to break in a manner to produce storm berms. Littoral transport of sediment by longshore currents is also limited by these topographic constraints.

Although much of the lowlands form a featureless plain, other sets of depositional, longshore beach ridges lie at elevations below 60 m between Churchill and Nelson rivers (Fig. 36). These ridges, concentrated at elevations of 60, 40, 25-30, and below 13 m, may indicate times when Hudson Bay was open during stormy months. These bunchings correlate with the delta-forming periods recorded on Churchill River but do not correlate with the climatic cycles proposed by Hillaire-Marcel and Fairbridge (1978) for eastern Hudson Bay. No cyclicity is indicated by assigning ages to the beaches using either the Churchill or the Nelson River emergence curves.

Flights of low gravel and shingle beaches directly east and south of Churchill have developed from the reworking of eskers and kames. Those in Caribou River area oriented at right angles to the modern coast are heavily modified eskers

Figure 36. Raised beach berms near Cape Churchill, and small fleche beaches. (NAPL A17406-65)

and De Geer moraines. In contrast, the beaches oriented perpendicular to the coast between Cape Churchill and Nelson River (Fig. 36) are true marine forms created by cellular nearshore currents and are unrelated to glacial landforms.

One of the more interesting aspects of present day sea level change is that, although the rate of emergence is only about 40 cm per century at present, the slope of the land is also extremely gentle (about 1 m/km). Tidal flats extend about 6 km into the bay beyond the present coast. At the present rate of emergence the Manitoba coast is moving out into Hudson Bay at a rate of about 400 m per century south of Churchill, and somewhat less than that north of Churchill, where the slope of the land is slightly steeper. In northeastern Manitoba relatively large changes in coastal configuration can occur in short periods.

Holocene evolution of lower Churchill River

Although several reaches of Churchill River may be reexcavated parts of an ancient river system, the present course of most stretches developed during postglacial time. The old parts of the river include the segments above Mountain Rapids, which have low banks and occupy a mature valley filled in with till and interglacial fluvial and organic beds. Similar infillings are found at The Fours and again downstream just below Limestone Rapids, although valley sides are steeper there. Although the present Churchill River may have intersected or flowed along parts of an old channel at these sites, the old river was probably much smaller than the present system, which rises in western Saskatchewan and drains an extremely large area. The present headwater area may have previously drained into the Seal River system, as suggested in the introduction to this report. The bathymetric trough north of the present mouth of the river (Pelletier, 1969) may be part of this river system. A more limited "Churchill" river system may have previously crossed parts of northeastern Manitoba but probably neither followed the course of the present river nor emptied into the sea at Churchill. Bathymetric contours suggest that the former river may have flowed in valleys located east of the mouth of Knife or Broad rivers. The lower Churchill today does not occupy a valley of regional proportions but rather is incised through the till plain and raised marine deposits. The incised portion extends from Mountain Rapids at the western end of the map area to about Long Island, at which point the banks fall away and the river broadens into the estuary.

For most of its length, Churchill River occupies the base of a chasm cut either into till or, between Portage Chute and Red Head Rapids, through till and Paleozoic limestone as deep as the Paleozoic-Precambrian unconformity. This chasm has vertical walls and is clearly postglacial in origin, as there is no sign of glacial shaping. The Precambrian rock forms rapids at the base of the chasm and also forms the river bed in other reaches (Fig. 37). The river has cut down as far as the more resistant rock and appears at present to be flowing over the old Precambrian paleoplain.

The river channel is 50-100 m deep. The modern river is about 600 m wide for the most part, and until the diversion, it did not meander across its flood plain (cross-section, Fig. 37). In contrast, the uppermost part of the valley slopes are much broader than the present river, being up to 3 km wide, which would seem to indicate one of three situations. Either in its early stages before significant downcutting the river was extremely broad and possibly very shallow; such a condition might occur in reaches that went through an estuarine phase. Alternatively, either the early river meandered across a width of about 3 km; or there has been considerable backwasting of the uppermost slopes by solifluction or by mass movements associated with oversteepening of silty till during downcutting.

Until the Nelson River project diverted the headwaters of the Churchill River, discharges were in the order of about 1400 m^3/s. At present the discharge averages less than 600 m^3/s.

Terrace levels and stages of downcutting

Several stages of downcutting are indicated by aggradation terraces with channels later incised into these levels. The earliest terrace (1 on Fig. 37) developed when sea level was at the marine limit. The terrace starts at 150 m just below Little Beaver River and grades to 145 m, the sea level of its time, at Portage Chute. The highest beach ridges in the Great Beach, in the vicinity of Churchill River, curve upstream into the valley, indicating that an incipient valley form was present from the time of deglaciation. The Portage Chute area was a marine embayment.

A second terrace (2 on Fig. 37) developed soon after and grades to a sea level that had fallen to between 135 and 140 m above present. Freshwater shells of the species *Sphaerium* in fine alluvial sand have been dated to 7670 ± 370 BP (GSC-3340; Nielsen and Kroker, 1982), which indicates that the terrace formed soon after deglaciation. A basal date from bog peat above the alluvium confirms that the age of the terrace is more than 5960 ± 100 BP (BGS-980; Nielsen and Kroker, 1982).

A segment of terrace (3 on Fig. 37) tilts more steeply than the previous ones and might have been deposited over a longer period of downcutting. Its age and the elevation of its base level are not apparent from the shape of its profile, but it could be grading to the 84 m sea level, which is marked by a widening of the valley downstream. Wood dated 3530 ± 100 BP (BGS-793) was taken from this terrace (Nielsen and Kroker, 1982). If the wood relates to the time of the terrace formation then base level was much lower, at about 45 m above present sea level, and the sea was about 50 km downstream.

A major gravelly aggradational surface with low slope developed at Limestone Rapids (terrace 4 in Fig. 37 and Fig. 38). This terrace, sloping from 76 m to about 55 m, may have formed about 4200 years ago when base level was near 55 m. A series of channels having steeper gradients are incised into the terrace, beginning at an elevation of 70 m and descending to 40 m. Projecting this gradient downstream, the incised channels link with a large, broad, low-gradient, aggradational surface descending from about 30 m to 23 m.

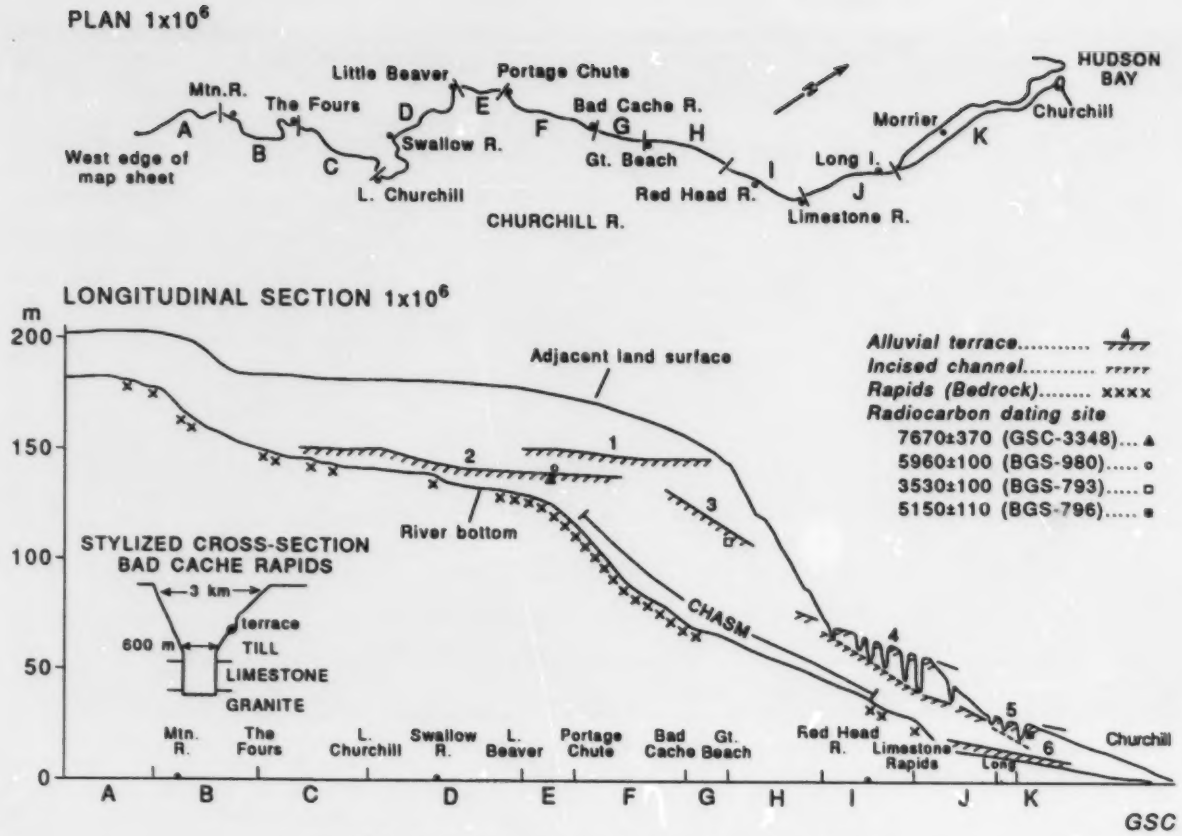


Figure 37. Longitudinal profiles and terrace levels, Churchill River.

This surface forms the top of Long Island (level 5) and adjacent parts of the main river bank. This aggradation level probably developed about 2200 years ago, although wood from this terrace level at the mouth of Deer River was dated at 5150 ± 110 BP (BGS-796). The wood may be a redeposited fragment.

The Long Island aggradation surface has been incised with channels grading to a base level at 15 m, which may either relate to a sea level about 1400 years ago at roughly 15 m or grade into the lowest major terrace, (6 on Fig. 37) lying at an elevation of about 7 m above present sea level.

Postglacial climatic changes

From their studies on pollen profiles and the location of relict stands of aspen and white spruce, Nichols (1967) and Ritchie (1962) concluded that the climate of northern Manitoba has varied over the course of postglacial time. Nichols' climatic reconstructions show that the forest-tundra margin, which now runs through the area covered by this report, was once 300 km farther north, and that summer temperatures between 6000 and 3500 BP were about 3°C warmer than present. Nichols proposed a cooling period between 3500 and 1500 BP, followed by a warming trend that lasted until 600 BP; cooler conditions persisted after that time.

Additional data resulting from this project fit Nichols' climatic trends and lengthen the climatic record. His proposed warmer periods coincide with the periods of major alluvial aggradation on Churchill River, which, according to terrace levels, occurred at the time of deglaciation about 7800 years ago, between 5400 and 4200 years ago (Limestone Rapids surface), between 3500 and 2200 years ago (Long Island surface), about 1400 years ago, and about 700 years ago (the lowest terrace). The increase in sediment loads suggests increasing erosion rates and an absence of permafrost throughout these time intervals. By the same reasoning, if the cessation of beach ridge accretion at 120 m on the Great Beach relates to a cut-off in the availability of sediment or to icing of Hudson Bay, then a period of colder climate started about 7000 years ago.

Basal sphagnum peat samples from bogs at four sites, near the northern limit of the boreal forest in northeastern Manitoba, yielded dates between 6000 and 6500 BP (Table 2). As bogs of this sort are rare in tundra areas they suggest that the boreal forest extended at least as far north as today during that time. The log extracted from the base of the peat at one Churchill River section (site 21, Table 2) is larger than most modern spruce in that area today. The pollen in the peat at Spruce Lake (site 58) suggests a fuller boreal environment than that at the site today, which lies along the forest-tundra transition.

Figure 38. Stereopair showing stages of downcutting preserved in terraces and abandoned channels of Limestone Rapids. (NAPL A17406-10, 11)

Also, woody forest peat was commonly encountered at the base of auger cores put down through the polygon-riddled tundra peat in the coastal lowlands, which now lie well beyond treeline. The sites with basal woody peat are found at elevations above 50 m. The woody layers indicate more extensive forest cover in the lowlands from the time of the Tyrrell Sea invasion until about 7200 years ago. The ice wedges and tundra vegetation, so prevalent in the area today, developed since that time. Dated *salix* and alder twigs, and other organic detritus from within the boreal forest of today (North Knife River), suggest that, by about 2500 years ago, the climate was cooler than at present.

Studies by Dyke (1988) and Hansell et al. (1983) at Churchill show that permafrost is developing today in the intertidal zone and in newly emerged areas. The sensitivity of the permafrost in this region to small temperature changes is demonstrated by the absence of permafrost in areas of willow thickets at these newly emerged sites. The thickets trap snow in winter and thus provide some thermal insulation during the coldest months. In fact the entire region is extremely sensitive to temperature changes much smaller than those experienced in postglacial time. Small changes in either vegetation, moisture, or snow cover appear to be sufficient to thaw or develop permafrost. Therefore, a small change in climatic regime produces major landscape effects. Perhaps the most readily visible change is the shape of the many small lakes in the lowlands, which continually change configuration in response to the melting or aggradation of minor amounts of ground ice.

ENVIRONMENTAL GEOLOGY AND MINERAL EXPLORATION

One purpose of this study was to provide an inventory of those aspects of the Quaternary geology pertinent to regional and environmental planning, and to economic development. Map 1617A shows the distribution of surface materials on a regional scale. The basic character of these deposits, described earlier in this report or in the Appendix, is summarized in the map legend. As such, the map and report provide a general basis for regional planning and a focus for site-specific studies.

Some aspects relating directly to economic development are addressed here, dealing first with permafrost and environmental issues related to the thermal sensitivity of the region. The second major section deals with land use concerns and engineering geology. The third section considers till geochemistry and mineral resources.

Permafrost

Distribution of permafrost

One of the prime concerns for construction or land use planning in this area is the incidence of permafrost and the amount of ground ice in frozen soils.

Climate is a basic factor in the formation and preservation of permafrost. Continent-wide studies have shown a broad relationship between the mean annual air temperature,

ground temperature, and permafrost distribution. Soviet studies have found that the limit between continuous and discontinuous permafrost generally corresponds to the -8.5°C mean annual air temperature isotherm, which in turn corresponds to a mean annual ground temperature of -5°C (Brown and Péwé, 1973, p. 75). This relationship is known to be valid for much of Canada as well. On the basis of this correlation between air temperatures and permafrost, the expected limit of continuous permafrost in this area should lie north of Churchill.

Field observations and numerical calculations (Dredge, 1979) indicate that, in the Hudson Bay lowlands, air temperatures and the incidence of permafrost do not correlate well, because of the low thermal conductivity of the extensive peat accumulations. Thus permafrost is much more widespread than expected on the basis of air temperatures alone.

Figure 39 shows the regional distribution of continuous and discontinuous permafrost. Discontinuous permafrost lies in the southwestern part of the region, in the area covered by forested bog. Permafrost may also be discontinuous in wet fen areas along a coastal strip between the Knife delta and Nelson estuary. Brown's records, for instance, indicate that permafrost is absent beneath one low wet site at Churchill, which he described as a "palsa depression" (Brown, 1978). Except for such small thermal islands, all areas beyond the forested bog lie within the zone of continuous permafrost. Continuous permafrost underlies the northern and eastern parts of the area, including the zone of polygonized peat and the mineral terrain north of Seal River. It also includes areas of newly emerged coast, where studies by Hansell et al. (1983) and Dyke (1988) indicate that permafrost is developing under present climatic conditions. The limit of continuous permafrost shown in Figure 39 is a modification of that shown on the Permafrost Map of Canada (Map 11, National Atlas of Canada), based on the results of field investigations with a frost probe and thermistor strings for this study, observations of Charles (1959) along the Hudson Bay Railway, and theoretical calculations (Dredge, 1979).

Parts of the forested boglands are thermally permafrost areas in that the mean annual soil temperature is less than 0°C. However, in some places, unfrozen water exists beneath frozen peats despite subzero temperatures because of capillary pressures in the fine-grained soils.

Thermal conditions in the zone of continuous permafrost

Permafrost thickness and ground temperatures

The following summary is based on studies and observations on ground conditions along the Hudson Bay Railway by Charles (1959), at Churchill by Brown (1978), and throughout the region by Dredge (1979; Dredge and Nixon, 1979).

Charles found the thickness of permafrost to be at least 45 m under Lake Roseabelle (Churchill). Brown (1978) gave a thickness of 60 m for permafrost at Churchill and noted that it thickens away from the thermal influence of Hudson Bay.

Brown found the average annual surface temperature of both rock and mineral soil to be between -2° and -4°C. At 4 m depth, soil temperatures in the Churchill area fluctuated seasonally between -3° and +1°C, whereas bedrock temperatures fluctuated between -10° and +5°C. The maximum summer ground temperature in peat-mantled mineral soil (polygonal peat over marine deposits) 80 km south of Churchill, also at 4 m depth, was -4°C (Dredge, 1979; Fig. 40 and additional thermistor observations).

Active layer depth

The depth of the active layer for a soil in this region can be accurately predicted using air temperature data if the physical properties of the earth materials are known. Predicted average depths of the active layer, calculated for soils in northeastern Manitoba (Dredge, 1979), are summarized in Table 3. Frozen peat in the polygonal peatlands commonly has a low water content (average 23% by volume; Dredge, 1979) relative to those determined for other areas (e.g., MacFarlane, 1969); therefore thermal conductivity is much lower, and the depth of annual thaw (about 50 cm) is much less than that predicted by other studies for other peats.

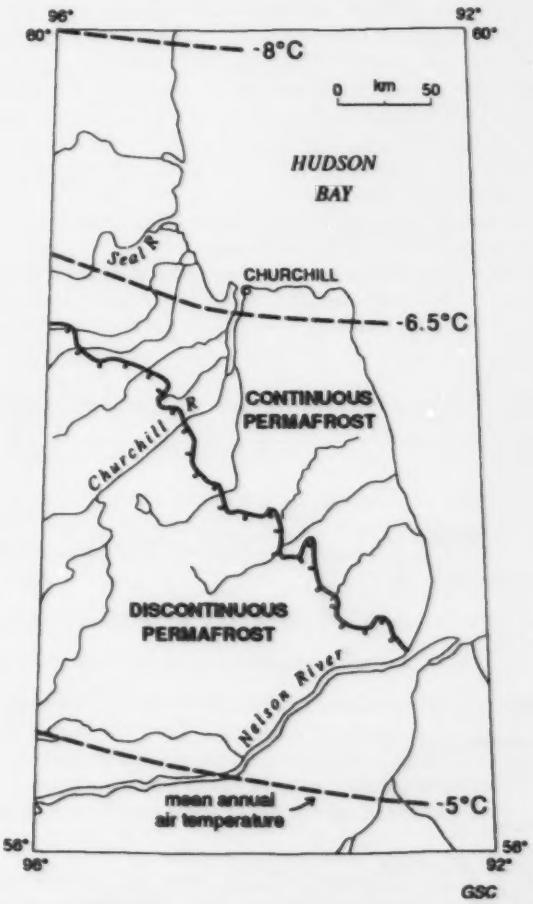


Figure 39. Distribution of permafrost.

The predicted values shown in Table 3 are calculated from a modified Stefan equation (Dredge, 1979; Dredge and Nixon, 1979) and agree closely with observed depths determined at calibration sites. The average active layer depth for dry polygonal peat was 42 cm for 1978, an unusually cool year. Moist peat has an active layer about 60 cm thick (Brown, 1978; Dredge, field measurements), which, because of greater thermal conductivity of wet peat, increases to more than 15 m in fens. Mineral soil thaws to a depth of about 40 to 60 cm north of Seal River (Dredge) or 46 to 90 cm at Churchill (Brown); rock thaws to a depth of 7 to 8 m (Brown).

The seasonal increase in thaw depth is important for scheduling vehicular travel, particularly over peatlands. Figure 41 shows the progression of thawing over the summer in relatively dry polygonal peat terrain. In general, thawing begins in early June in this area and reaches a maximum depth by the end of August. The rate of thawing is rapid at the beginning of the season but slows considerably thereafter.

Three significant conclusions about the upper thermal regime can be summarized by examining the vertical temperature profiles and progressive seasonal thawing calculations. First, thawing does not extend through polygonal peat into the subsoil. Secondly, in polygonal peatland, subsoil temperatures are sufficiently below freezing to maintain the underlying clayey mineral soil in a frozen state despite capillary moisture. Thirdly, for wetter peats, which have a higher thermal conductivity, or for thinner peat accumulations, temperatures are warmer and thawing may penetrate to the mineral substrate.

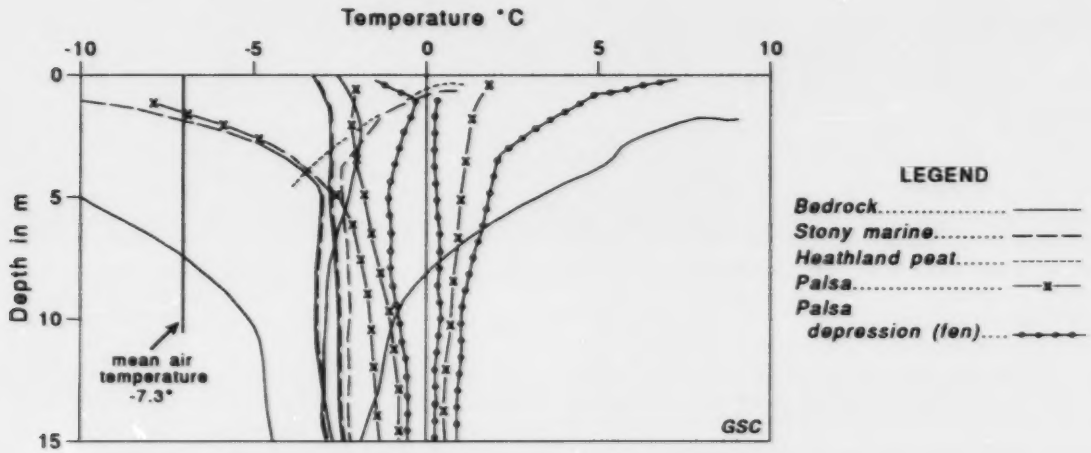


Figure 40. Mean annual ground temperatures for Churchill (after Brown, 1978 and Dredge, 1979).

Table 3. Physical properties of peat, and active layer thicknesses (calculated from the Stefan equation)

Material		Water content (% of volume)	(% of wt)	Density (bulk, dry) ($g \cdot cm^{-3}$)		Thermal conductivity (K) (millical·cm^{-1}·s^{-1}·$°C^{-1}$)	Reference	Predicted thaw depth at Churchill (cm)
Frozen peat-	dry	22	619	0.24	0.04	0.23	Dredge, 1979	50
	moist	50	750	0.4	0.08	2.3	MacFarlane, 1969	107
	wet	90	1500	1.2	0.02	4.8	MacFarlane, 1969	115
Ice		100				5.0		
Unfrozen peat		50				0.7	MacFarlane, 1969	50
		90				1.3	MacFarlane, 1969	60
Water		100				1.36		
Frozen or unfrozen silt-clay		10-30				4-8	Sanger, 1963	270-250

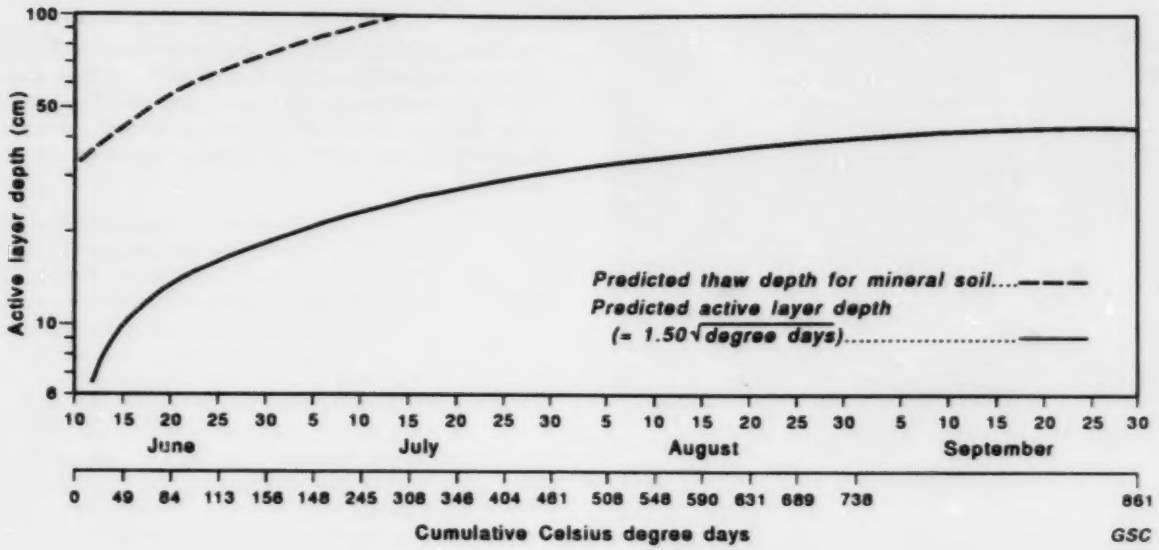

Active layer depth (cm)
100
50
10
8
Predicted thaw depth for mineral soil....
Predicted active layer depth
(= 1.50√degree days).....
10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30 5 10 15 20 25 30
June
July
August
September
0 49 84 113 156 148 245 308 346 404 461 508 548 590 631 689 738 861
Cumulative Celsius degree days
GSC

Figure 41. Seasonal progression of thawing in peat.

Thermal conditions in discontinuous permafrost

The distribution and character of permafrost in the discontinuous zone is less well known, but frost probing has indicated that areas with permafrost are much more prevalent than those without. Areas with permafrost correspond closely to areas with forested peat cover, whose thermal condition is manifested by frost heaved mounds and thermokarst depressions on the surface, by mudboils, and by palsa in adjacent fens. Depths of the active layer are commonly about 60 cm by the end of August and are almost that depth by the end of July. Soil temperatures are probably near 0°C, because capillary moisture in clayey soils remains unfrozen. Fen lands were thawed to some depth greater than 3 m, the limit of the probe.

Ground ice

Information on the distribution and type of ground ice comes from the following sources: the distribution of ice wedge polygons, palsa, and retrogressive thaw flow slides visible on airphotos; smaller features such as mudboils and frost blisters seen on the ground; and subsurface investigations using manual and power driven augers. Both the forested bog peat and polygonized peat are icy. The polygonized areas contain large amounts of segregated ground ice in the form of ice wedges (Fig. 42). In addition to this, the average ice content of the peat between ice wedges is about 22% by volume (660% by dry weight). The active layer in many places is well drained and dry, but below this depth ice contents are fairly high. Cores show that this ice occurs as coatings around organic fibres, small crystals, thin laminae, and layers of white ice 2 to 10 cm thick. Commonly an icy layer lies at the contact of the peat and mineral soil. Cores taken through forested bog peat show similar ice types, ice contents, and ice distributions.

Ice contents of the mineral soils underlying the peat are highly variable. Silty and clayey deposits have relatively high ice contents in their upper 3 m (the limit of most measurements), but visual observations and limited data from longer boreholes indicate that ice content tapers off at greater depths. The general absence of massive slope failures along rivers supports this idea. In silty tills and some glaciolacustrine clays shallow auger cores revealed fairly high ice contents in the form of ice coatings, crystals, laminae, and layers of segregated ice. At more than half the sites the extracted core flowed as a slurry upon melting, the water equivalent being 30 to 40% of the soil weight. In some places capillary moisture remained in its liquid state, despite subzero soil temperatures.

Palsa 2 to 5 m in diameter (Fig. 23) indicate the presence of massive bodies of segregated ice in stringed fenland near the coast, and in a few fens farther inland.

The ice content of bouldery till appears to be very low in areas not covered by peat, moderately low in the silty marine pelite, and nil in eskers and beach ridges.

Thermal sensitivity of peatlands

Development of tundra ponds and thermokarst lakes

Observations on the changing appearance of the peatlands from year to year, and calculations on the physical effect of minor changes in temperature or moisture conditions suggest that there is a delicate balance between the development and degradation of permafrost in the polygonal peatlands.

The following stages (0-8) outline the development of large thermokarst lakes in polygonal peat terrain under average conditions. They explain sequentially what was

Figure 42. Ice wedge troughs. (GSC 203121-C).

observed spatially in the field. At any given site, which may be wetter than average or have a shallower peat cover, one or more steps may not have occurred.

This sequence differs from others that have appeared in the literature in that it considers landforms and processes occurring in peat, whereas others deal primarily with loams or marine sediments (cf. Johnston and Brown, 1964; Hussy and Michelson, 1966; Black, 1969; Czudek and Demek, 1970; Sellman et al., 1975). Peaty material has different primary physical characteristics (e.g., density and permeability) and a greater range of moisture contents. Consequently, peat has more variable thermal transmission properties in its various frozen-unfrozen and wet-dry states. As a result peatland thermokarst features differ in form, magnitude, and development sequence from those found in inorganic terrain. For example, the baydjarakh and dujoda developmental stages (Czudek and Demek, 1970) are absent in peatland, thermokarst valleys are not produced, and lakes have maximum depths of about 4 m.

Stage 0 Equilibrium condition. In the initial case, peat in this terrain is generally dry (22% moisture by volume) and therefore has a low conductivity (K about 0.23, Table 3). Seasonal thawing extends only to about 50 cm and does not penetrate through the peat, which is 150 to 200 cm thick in most places.

Stage 1 Thawing of ice wedges. Thermokarst development begins with the thawing of ice wedges that have become exposed through a variety of factors, including rupturing of the overlying peat during growth of the wedge. Melting proceeds along the wedges; ice wedge troughs, and particularly where troughs intersect, develop into water filled depressions (1 in Fig. 43).

Stage 2 Saturation of peat within polygons. Water from depressed ice wedge troughs seeps into the adjacent relatively dry active layer of the peat and freezes in winter. During the following season, these zones, now having higher moisture contents and hence higher thermal conductivities (K about 2.3 to 4.8), experience an increased depth of thaw (up to 115 cm). Ice melts in the polygons, some subsidence occurs (20 to 40 cm observed), and small pools of water form over these polygons with lowered centres (2 in Fig. 43).

Stage 3 Development of ponds. Once the depth of water in the pools exceeds about 25 cm, the pool acts as a radiation trap in summer and the thawing process accelerates. Thawing and subsidence proceed radially from the pool, but lateral thawing exceeds vertical thawing, for two reasons. First, the active layer beneath the pond gradually reaches an equilibrium thickness, and no further downward thaw occurs until the characteristics of the heat source or transmitting medium change. Secondly, the thermal conductivity is greater, and the rate of heat flow is therefore faster in a refrozen saturated active layer than in the underlying peat having lower ice content. The result in both cases is the expansion of pools to form the shallow flat-bottomed ponds (3 in Fig. 43) that are so widespread in the area. These ponds are between 50 and 70 cm deep.

Stage 4 Expansion of ponds. As the pond grows, both lateral and vertical thawing increase, more subsidence by melting of grounded ice occurs, and ponds coalesce. As the ponds deepen, thawing extends into the mineral substrate at about 200 cm.

Stage 5 Development of lakes. Further lateral expansion of large ponds occurs by the mechanical processes of ice ramming during spring break-up and wave battering and undercutting of peat banks in summer, combined with the thermal erosion of ice wedges and ground ice adjacent to the lakes. In some cases lakes have expanded preferentially along a southerly or southeasterly axis, in response to the prevailing winds from the north and northwest. Not all lakes develop in this manner, however, since the direction of preferential thawing is also related to random occurrences of massive

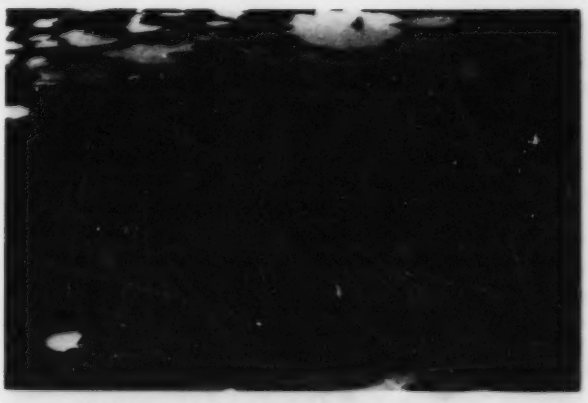


Figure 43. Stages in the development of thermokarst ponds: (1) water-filled ice-wedge troughs; (2) pools; saturated polygons; (3) ponds; (4) expanded ponds; and (5) lakes. (GSC 205283Q)

ground ice and to elongated topographic highs (related to beach ridges) in the underlying mineral substrate. Both thaw depths and lake depths are greater where mineral soil is near the surface than in adjacent areas of deeper peat because the thermal conductivity of the mineral soil is greater (K = 4 to 8).

Stage 6 Coalescence of lakes. Expansion of lakes occurs by the coalescence of adjacent ponds (Fig. 44). Large lakes tend to lose any pre-existing elongation during this stage. The lakes are irregular in shape, and the shorelines form a series of arcs that demark the outlines of former ponds.

Stage 7 Cessation of lake growth. The expansion of lakes is halted in several ways:

a. A general vertical geothermal equilibrium is reached between seasonal freezing and depth of thawing.

b. As peat banks around lakes and ponds collapse, a layer of peat fibres is dispersed across the lake bottom. The wet, unfrozen peat sediment gradually forms an insulating layer that reduces the rate of heat penetration and thawing.

c. Subsidence is limited by the volumetric excess ice originally available. Once this excess is depleted, thermokarst subsidence halts.

d. Ponds drain when spring flooding, natural melt, or migration of water courses cause ice wedges connecting lakes to melt to a level below the surface of the higher lake. Drainage also occurs when the frozen confining bottoms or sides of ponds thaw following local thickening of the active layer. Many scars of lakes are visible on airphotos of this area. If the water table drops slightly, paludification commonly occurs; if lakes drain completely, grass and shrub willow commonly colonize the wet centres and drier margins of the lake beds, respectively.

Figure 44. Large lakes in polygonal peatlands (stage 6). The arcuate outlines indicate that the lakes have formed by the coalescence of ponds. (GSC 203121-K).

Stage 8 Thermokarst ponds and thermal sensitivity. Visual evidence for the active development and demise of tundra ponds and thermokarst lakes in the area suggests that the processes are now in a steady state. This equilibrium is sensitive, however, for two reasons. First, many tundra pools are just at the point at which, if a marginal increase in thawing occurs, progressive thermokarst development into the mineral substrate will begin. Because of the higher conductivity of the mineral soil (Table 3), rapid increased thawing and subsidence can occur in icy sediments. Secondly, the thermal conductivity of peat is highly sensitive to changes in moisture content. Doubling the water content will increase the thermal conductivity of frozen peat by an order of magnitude. At present, the polygonal peat terrain is atypically dry relative to moisture contents in peat in other regions and hence has a very low thermal conductivity. However, any natural or artificial process that impedes soil drainage may cause deep thawing, both in the peat and through the peat into the mineral substrate, with the possible accelerated expansion of thermokarst ponds and lakes over a broad area.

Engineering problems related to permafrost conditions

This region is particularly sensitive to changes in the thermal regime because ground temperatures are generally only slightly above or below zero. Changing the soil temperature by a few degrees may create a change of state.

Heave and subsidence caused by ground ice

Many of the difficulties associated with construction in continuous permafrost, and especially in discontinuous permafrost, are related to the aggradation or degradation of bodies of ground ice. Small disturbances leading either to the removal of the peat cover, or to changes in moisture content of the soils, may cause mounding where ground ice (particularly ice lenses or massive ice domes) accumulates and subsidence where ground ice melts out. These processes occur naturally: they are particularly apparent along river banks and over areas covered by polygonized bogs. In the latter area coalescence of tundra ponds and thawing of ice wedges change the thermal conductivity of the peat and accelerate melting (Dredge, 1979). Conversely, draining of ponds, by the melting of ice barriers, leads to thermal conditions condusive to the growth of ground ice. Similar changes, on a larger scale, occurred where drainage was impeded during construction of the Hudson Bay Railway.

Liquefaction of soils

Most of the silty and clayey soils are of low plasticity. Liquid limits range from 20 to 24 and plastic limits are between 8 and 9. Moisture contents, not including large ice lenses, are commonly at or less than the liquid limit at depth but are generally about 30% in the upper 5 m, where there are moderate to high amounts of laminar segregated ice. Moisture contents in this zone exceed the liquid limit. Newly excavated slopes and freshly eroded river banks are therefore potentially

unstable and will remain unstable until a new thermal equilibrium is reached. The problem is exemplified by the active thaw flow slides along North and South Knife rivers, which prevail where icy glaciolacustrine silts lie near the ground surface, and by several old landslide scars along Churchill River.

Seasonal soil churning and solifluction

All mineral soils except for those of eskers, beach ridges, and kames have enough fines to render them susceptible to seasonal frost churning. The activeness of this process is manifested by the proliferation of unvegetated mudboils between 50 and 100 cm in diameter on the surfaces of bouldery till, silty till, lacustrine deposits, and stony marine pelite, both above and below the treeline. Solifluction lobes are common features north of the treeline, and solifluction is active in degradation of the upper slope facet of the banks of Churchill River.

Frost heave of bedrock

Bedrock is also susceptible to frost action. Extensive areas in the general vicinity of Seal River are covered with frost shattered rock (Fig. 5). At least some of this shattering occurred in recent times, as indicated by the sharpness of the edges of thrust blocks and the absence of lichens on thrust faces. In addition, measurements on the rate of seasonal movement of rock panels along bedrock joints blocks at Churchill (Dyke, 1984; Fig. 45), and on the rock burst features described under *Bedrock Outcrop* in this report (Fig. 11), suggest that rock heave is an active and spectacular process in this area. Dyke attributes the movement observed to the trapping of water and build-up of pore pressures in joints during freeze-back. Some heaving also results from the volumetric expansion of water as it turns to ice. The heaving process is self perpetuating in that once joints are widened, surface gravels and exfoliated bedrock slabs can fall into the crevasses, keeping the cracks open. Water therefore penetrates more deeply in succeeding years, progressively opening deeper joints.

Figure 45. Heaved and split rock panel at Churchill airport. (GSC 203603-C)

Recommendations

Charles (1959, p. 135) compiled a list of things to do and situations to avoid based on his experience in building the Hudson Bay Railway. These recommendations are applicable to all construction activity in the area. He stated:

"1. Before ground surveys are commenced to establish a proposed railway, air photos should be analyzed and interpreted to indicate where permafrost may occur and to what extent and to locate possible deposits of granular materials.

2. Air photographs and photogrammetry should also be used to aid in selection of the best route. Careful consideration of drainage features is particularly important.

3. In territory where permafrost occurs in comparatively small isolated areas – "Islands" – such areas should be avoided to the extent practicable in relation to distance and ruling gradients etc.

4. Permafrost on a side-hill slope can become very troublesome.

5. Where it is not practicable to avoid excavating in permafrost for construction of a railway roadway, excavations should be extended to a depth of 3 feet to 5 feet below sub-grade, then backfilled immediately with comparatively dry materials, preferably granular, if available within reasonable hauling distance.

6. Sides of cuts in permafrost should be excavated to very flat slopes, as a precaution against material sliding and obstructing drainage ditches.

7. Drainage is always important, this especially so in areas of permafrost. Off-take ditches should be excavated and well maintained to prevent accumulation of water against side-slopes of embankments, particularly where they are built on permafrost, as water in contact with it will cause thawing.

8. Special care is necessary in selecting sites for bridges and culverts and type of structure with respect to site conditions. Whereas first class foundations are essential for rigid type structures, such as steel bridges on concrete structures, it is not so serious if some distortion occurs in a timber trestle or a cedar box culvert; they will remain functional.

9. Cross-section area of culverts should be comparatively large to facilitate cleaning in event of an accumulation of ice.

10. In areas where permafrost is general and there are no great changes in topography, such as the tundras, design the location to obtain a roadway to be entirely embankment, if practicable to do so.

11. Relative telegraph and telephone lines should be erected on tripods of cedar poles, set on the surface. [Fig. 46].

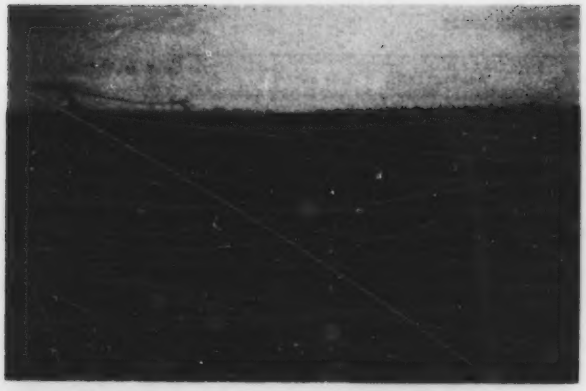


Figure 46. Tripole support structures for hydro lines: a simple, effective means of compensating for frost heave and subsidence. (GSC 204860)

Excavations should be restricted to off-take ditches and minor levelling on the railway right-of-way just sufficient to permit track to be laid. Then the track should be lifted by trainfill, to build up embankments on undisturbed permafrost.

Finally, when constructing where permafrost is general, preserve this condition, build on it, do not excavate into it, except for essential drainage to prevent accumulation of water and relative thawing."

Buffering capacity of calcareous soils in cold regions against effects of acid rain

A subject of considerable concern in recent years is that of acid rain, and the capacity of soils to buffer its effects. Maps of sensitivity to acid rain in parts of central and eastern Canada (Shilts, 1981), constructed on the premise that calcareous soil (particularly silty soils) and carbonate bedrock types have a high buffering capacity, show that the Hudson Bay lowlands area has a high buffering capacity. Results from investigations on the nature and depth of carbonate leaching in northeastern Manitoba (Dredge, 1988a), however, indicate that calcareous soils in boreal areas are not necessarily good buffers because carbonate ions are not available for cation exchange. Caution is required in assessing buffering capacity on the basis of carbonate contents alone. Although acid rain is not at present a problem in northeastern Manitoba, results of studies here generally apply to much of the Hudson Bay lowland and adjacent areas where the main surface materials are carbonate bedrock or fine-grained calcareous till, glaciolacustrine or glaciomarine deposits, and where permafrost is present.

Cores were taken in frozen (permafrost) and unfrozen soil, and carbonate contents were determined at various depths. The results, summarized in Figure 47 (from Dredge, 1988a), show that calcareous tills and related soils in peat-mantled areas have been leached to a considerable depth and degree. The depth of leaching differs for frozen and unfrozen soils but in both cases leaching is greatest at the surface and decreases with depth. There is no zone of carbonate accumulation. The results also show that the maximum depth of leaching of unfrozen soil is about 3 m. Frozen soils are leached only to about 60 cm, the depth of the active layer but, because this layer is the main zone of meteoric groundwater flow, much of the available carbonate has already been leached.

Thus unfrozen, calcareous soils in the region can neutralize the effects of acidified surface water as it migrates through. Unfrozen soils thus have a high buffering capacity. Where permafrost is present, however, water circulates mainly in the active layer, which has already been substantially leached. Carbonates in the frozen subsoil do not act as buffering materials. In areas of continuous and discontinuous permafrost, therefore, a calcareous soil should not be assumed to have a high buffering capacity.

Land use concerns

Sand and gravel resources

The principal potential sources of aggregate are the widespread glaciofluvial and marine littoral deposits and bouldery till. However, not all these deposits are useful as

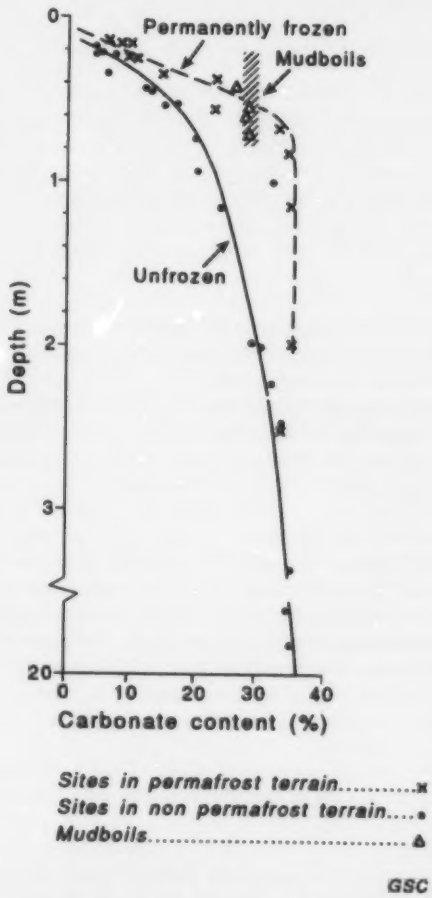


Figure 47. The leaching of calcareous soils in continuous and discontinuous permafrost (after Dredge, 1988a).

Table 4. Engineering index properties of fine grained sediments

	Carbonate		Grain size (gravsandsiltclay)		Atterberg Limits		Bulk density	W
Material	%	Range	%	Range	WL	WP	g/cm³	%
Grey till	25	(3-52)	4/36/40/20	(0-13/22-77/5-73/0-39)	23	14	1.86-2.20	15-30
Brown till	30	(7-48)	3/28/48/21	(0-5/1-43/41-90/9-29)	24	15		
Lacustrine clay	23	(2-46)	1/18/63/18	(0-3/0-30/33-94/4-33)	24	16	1.84	25
Marine silt	28	(17-47)	0/40/47/13	(0-5/8-75/16-78/5-19)	19	16		

aggregate; many are shallow, isolated, of undesirable composition, and difficult to extract below frozen peat (Dredge and Nixon, 1980).

Bouldery till is a widespread surficial material in the northern part of the area and consists primarily of sand and gravel of "granitic" (i.e., Precambrian, noncalcareous rock types) composition. Between 30 and 40% of the matrix, however, consists of silt and clay fines, which make the gravel frost-susceptible. Large amounts of associated boulders may make this material difficult to extract. The conjugate crevasse fillings are composed of better sorted sand and gravel of the same composition as the till, and this material has fewer fines and less boulders.

Eskers, commonly 10 m high and running for distances of 25 km, provide a major source of sand. North of 58°N the eskers are composed of "granitic" sand or gravelly sand; south of this latitude they are largely composed of calcareous silty sand. Massive nodes along eskers and kames, such as those forming Twin Lakes and Knight's Hill, are prime sources of pebble and cobble gravel.

Raised beaches are composed mainly of sand and sandy gravel. North of 59° and at low elevations between Button Bay and Cape Churchill, they contain much gravel, although the deposits are generally shallow. In the north, they are composed of "granitic" particles; near Churchill they are a mixture of carbonate and "granitic" lithologies and much of the material is in the form of limestone or mudstone flags.

Sand and gravel in varying amounts and of mixed composition are also the main component of the coastal beach ridges between Cape Churchill and Port Nelson, and those which extend inland sporadically as far as the Great Beach. These deposits are 1 to 3 m thick. In the ridges near the coast, about 90% of the pebble fraction is carbonate; those inland have progressively decreasing amounts of carbonate.

The Great Beach, a compound ridge 200 km long and up to 500 m across, cuts across the adjacent silty marine and lacustrine plains. Because it stands 2 to 6 m above the neighbouring swamps, it serves as a transportation corridor as well as a source of aggregate. It consists of sorted sand, commonly underlain by gravelly sand, interspersed with patches of sandy gravel. South of Churchill River the pebble clasts are 50% carbonate; north of the river they are mainly gneissic or granitic. The feature is cored in some places by a silty till and hence the volume of potential aggregate may be much less than its size suggests.

Sandy and gravelly blanket beach deposits underlie much of the organic terrain below an elevation of 150 m. Despite their widespread occurrence, most blanket deposits are poor sources of aggregate because they are commonly shallow, contain muddy sediments from underlying silt that have been incorporated by cryoturbation, and are overlain by 2 to 4 m of perennially frozen peat.

Geotechnical properties of materials

Basic geotechnical characteristics of materials, provided in the appendix under specific material types and stratigraphic units, are summarized in Table 4. Peters and McKeown (1976) reported similar textural characteristics and Atterberg limits for silty tills along Nelson River. They found water contents of 8 to 13% at depth, whereas those determined by us for tills nearer the ground surface and for lacustrine clays are slightly higher. The till reported by Peters and McKeown is correspondingly slightly more dense. They obtained bulk density values between 2.2 and 2.4 g/cc, whereas our results are closer to 1.9 to 2.2 g/cc. Peters and McKeown found the silty tills to be relatively incompressible, and the overlying lacustrine and marine clays to be moderately compressible. The till had an in situ permeability of 10^{-8} to 10^{-9} cm/sec. They pointed out the potential problem of sand and gravel layers within the Nelson River till as potential seepage or failure zones. These layers are the subglacial and interglacial units observed in many exposures within the study area.

Peat resources

Northeastern Manitoba is covered extensively with peat considered to be of marketable quality (Cameron, 1948). However, because the peat is frozen below a depth of about 0.5 m, the workings would have to cover a large area, as only the surface layer could be extracted during one year's operations. Distance from existing markets is a handicap but is compensated, to some degree, by proximity to the Hudson Bay railway and the port of Churchill.

Till geochemistry

One hundred and thirty-two till samples, collected over an area of about 48 000 km^2, have been analyzed for base metals and uranium. Because this project was not directly oriented towards drift prospecting, the sampling density is too low for detailed geochemical interpretations of the data. However, the results provide estimates of background values characteristic of the region, show major differences resulting from differences in ice flow direction and source rocks, and indicate a few areas where more detailed geochemical sampling might be warranted. Extensive areas are drift-mantled and rock outcrop is scarce.

Methods

Most tills were collected either from depths of about 0.5 m from hand-dug pits in unfrozen ground or from power auger cores in frozen ground. In samples taken from river bank cuts, only the results from the top till are reported here. In the laboratory, the samples were centrifuged and the <2 mm fractions were analyzed for copper, lead, zinc, cobalt, nickel, chromium, molybdenum, manganese, iron, arsenic, and uranium. Analytic procedures follow the style and rationale of previous geochemical studies at the Geological Survey of Canada (Klassen and Shilts, 1977). Base metals were analyzed using atomic absorption techniques after LaForte reverse aqua regia extraction; arsenic values were derived using colourimetric standards, and uranium values were determined by fluorometric methods.

Till types, bedrock, and ice flow

Two main bedrock types underlie this area: the granitic, gneissic and metavolcanic rocks of Precambrian age in the north and west (Fig. 48), and carbonate sedimentary rocks of Paleozoic age in the southeast. A thin blanket of till covers the Precambrian rocks; thick drift covers the Paleozoic sediments. Ice flow north of North Knife River was towards the south and south-southeast. Tills associated with this flow are sandy because of incorporated medium-textured Precambrian rock components; they are also generally thin. Most samples from this area are taken from ribbed moraine areas, where drift may have been carried by glaciers only for short distances. Consequently, metal values may reflect concentrations in the bedrock underlying the sites or nearby bedrock directly north of them. Based on garnet dispersal trains from garnetiferous gneiss outcrops, sandy till from other landform types has been transported, on average, between 1 and 5 km (Dredge, 1981a). In contrast, ice flow in the central and southern parts of the area was towards the west. Tills associated with this flow are mainly silty and are composed primarily of carbonate rock types, miscellaneous components inherited from underlying tills, and a minor amount of far travelled metasediments. The silt till is up to 40 m thick. Metal values determined from upper zones of the silty till reflect average concentrations from local to distant easterly sources and do not necessarily reflect characteristics of the underlying bedrock.

Base metal concentrations

Figure 49 shows frequency distributions and class mean values of base metal values for each element. Anomalies, or elevated values, are here defined as those lying at or beyond the 95th centile of the frequency distribution. For northeastern Manitoba the boundary between background and anomalous values is 6 ppm for uranium, 140 ppm for zinc, 7 ppm for molybdenum, 25 ppm for cobalt, 100 ppm for copper, 900 ppm for manganese, 70 ppm for nickel, 90 ppm for chromium, 25 ppm for lead, 9 ppm for arsenic, and 6% for iron. The histograms (Fig. 49) show that, for some elements, the sandy till and silty till form two significantly different subgroups within the northeast Manitoba sample population. Background means for uranium, copper, chromite, and molybdenum are higher in sandy till than in silty till, although means for the remaining elements are similar. Most anomalous values in both cases are within the sandy till.

Location of anomalies

The precise location of all samples, the base metal values for each sample site, and contoured distribution patterns of each element are presented in Geological Survey of Canada Open File 931 (Dredge, 1983b). Figure 48 shows the distribution of sampling sites and locations of anomalies for northeastern Manitoba calculated from the sample population from that area. Sites anomalous over a broader area of northern Manitoba are shown in Dredge (1983a). Almost 25% of the samples are enriched in some element, and most of these lie in the northern part of the region. Seventeen of the sites have anomalous values in more than one element, and four sites are enriched in four or more. Base metal and uranium anomalies are much more abundant in the sandy tills north of Seal River than they are in sandy tills to the south, or in silt tills. Because most of these samples were taken from ribbed moraines, they reflect relative metal concentrations in the nearby bedrock. Uranium anomalies are confined to tills overlying intrusive rocks in this region, chiefly fluorite bearing granites, monzonites, and granodiorites. The greatest anomaly lies at the south end of Caribou Lake. The sites with high uranium values in till coincide with radiometric highs reported by Schledewitz (1986), although not all sites with high radiometric readings showed uranium in the till. Molybdenum, lead, and zinc anomalies are common in tills overlying both Archean and Proterozoic rock types. Copper anomalies in till are associated more with Archean granitic and gneissic rocks than with younger rocks, although Schledewitz (1986) reported copper and zinc sulphides from the younger volcanic complexes as well. Iron is also found in the volcanic and greywacke complexes. Nickel, cobalt, and chlorite are common near Proterozoic granites. Most arsenic anomalies relate, like iron, to the Precambrian volcanic complexes. The occurrence of arsenic within and down-glacier from the lower Seal River volcanic complex is especially significant because similar occurrences have been related to high gold values in the same bedrock complex at Great Island about 20 km to the west (Dredge and Nielsen, 1986; Nielsen, 1987); Schledewitz (1986) reported gold directly from the lower Seal River area.

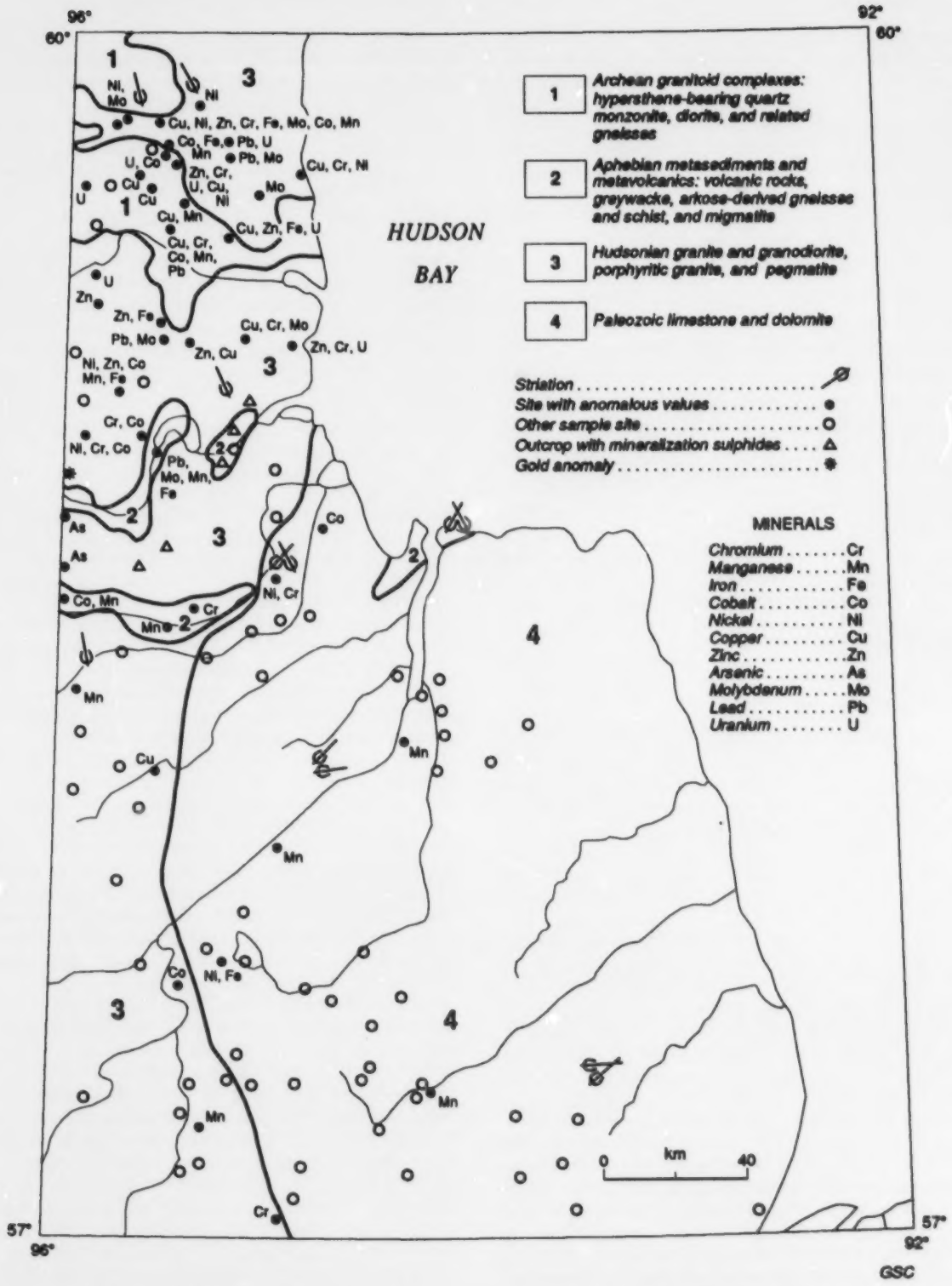


Figure 48. Base metal, uranium, and gold anomalies in northeastern Manitoba. (Geological units after Manitoba Mineral Resources Division, 1979).

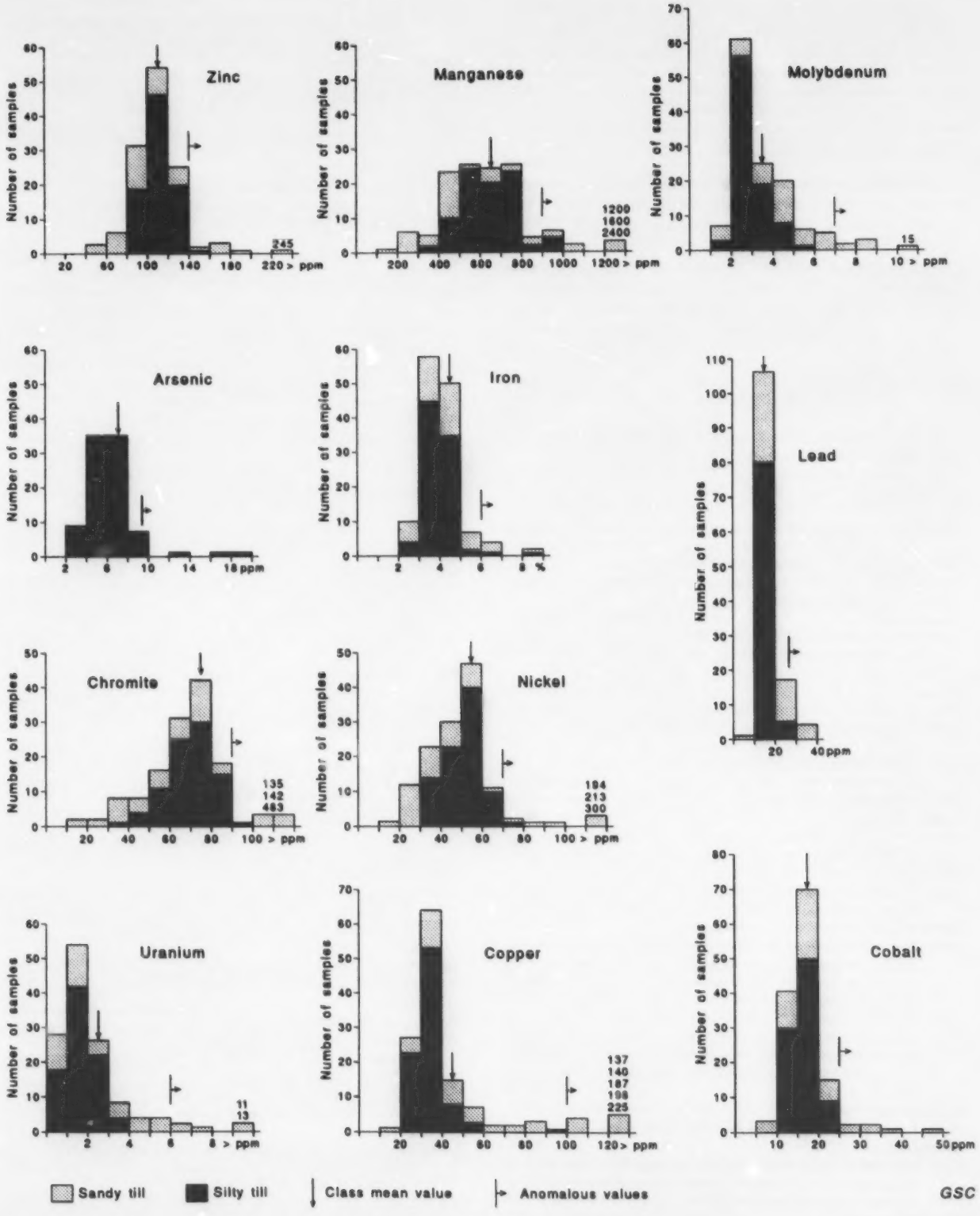


Figure 49. Base metal and uranium values.

Manganese anomalies occur in the sandy till (combined with other base metals) and in the silty till. Those in the silty till may result in coprecipitation occurring preferentially in marine carbonate sediments, which are source rocks for the till.

ACKNOWLEDGMENTS

Lynda A. Dredge directed the project, ran traverses, compiled the map, and wrote the final version of the report. F. Mark Nixon directed extensive drilling operations and prepared half the traverses. Serge Paradis mapped and described the area between Button Bay and Cape Churchill north of 58°30′ as part of a master's thesis (Paradis, 1980). M. Hume and M. Mihychuk also assisted with field work. The Northern Studies Centre, Churchill, provided accommodation in 1978 and 1979.

REFERENCES

Alcock, F.J.
1916: Lower Churchill River Region, Manitoba; Geological Survey of Canada, Summary Report for 1915, p. 133-136.
1920: The Reed-Wekusko map area, northern Manitoba; Geological Survey of Canada, Memoir 119, 47 p.

Ambrose, J.W.
1964: Exhumed paleoplains of the Precambrian shield of North America; American Journal of Science, v. 262, p. 817-857.

Andrews, J.T., Shilts, W.W., and Miller, G.H.
1983: Multiple glaciations and deglaciations in the Hudson Bay lowlands, Canada; Quaternary Research, v. 19, p. 18-37.

Barnett, D.M.
1970: An amendment and extension of tide gauge data analysis for Churchill, Manitoba; Canadian Journal of Earth Sciences, v. 7, p. 626-627.

Bell, R.
1879: Report on the country between Lake Winnipeg and Hudson's Bay, 1878; Geological Survey of Canada, Report of Progress for 1877-78, part 6.
1880: Report on explorations on the Churchill and Nelson Rivers and around Gods and Island Lakes; Geological Survey of Canada, Report of Progress for 1878-79, part IV.

Black, R.F.
1969: Thaw depressions and thaw lakes, a review; Biuletyn Peryglacjalny, v. 20, p. 131-150.

Bostock, H.H.
1969: Precambrian rocks of the Deer River map area, Manitoba; Geological Survey of Canada, Paper 69-24, 37 p.

Brown, R.J.
1978: Influence of climate and terrain on ground temperatures in the continuous permafrost zone of northern Manitoba and Keewatin, Canada; Proceedings, 3rd International Permafrost Conference, Edmonton, p. 15-21.

Brown, R.J. and Pewe, T.L.
1973: Distribution of permafrost in North America and its relationship to the environment: a review, 1963-1973; North American contribution to the 2nd International Conference on Permafrost, Yakutsk, p. 71-100.

Cameron, E.L.
1948: Peat moss in Manitoba; Manitoba Mines Branch, Bulletin 48-1, 11 p.

Charles, J.L.
1959: Permafrost aspects of Hudson Bay railroad; Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, December, p. 125-135.

Clayton, L. and Moran, S.
1982: Chronology of Late Wisconsinan glaciation in middle North America: Quaternary Science Reviews, v. 1, p. 55-82.

Craig, B.G.
1969: Lateglacial and postglacial history of the Hudson Bay region; Gelogical Survey of Canada, Paper 68-53, p. 63-77.

Czudek, T. and Demek, J.
1970: Thermokarst in Siberia and its influence on the development of lowland relief; Quaternary Research, v. 1, p. 103-120.

Davidson, W.L.
1966: Caribou River map area; Geological Survey of Canada, Paper 65-25, 6 p.

DiLabio, R.N.W.
1978: Occurrences of disrupted bedrock on the Goulburn Group, eastern District of Mackenzie; in Current Research, Geological Survey of Canada, Paper 78-1A, p. 499-500.

Dionne, J.C.
1983: Frost heaved bedrock features: a valuable permafrost indicator; Géographie Physique et Quaternaire, v. 37, p. 241-251.

Dredge, L.A.
1979: Thaw depths and permafrost in polygonal peat terrain, Hudson Bay lowlands, Manitoba; in Current Research, Geological Survey of Canada, Paper 78-1C, p. 27-30.
1981a: Trace elements in till and esker sediments in northwestern Manitoba; in Current Research, Geological Survey of Canada, Paper 81-1A, p. 377-381.
1981b: The leaching of carbonates in discontinuous permafrost, boreal Manitoba; in Current Research, Geological Survey of Canada, Paper 81-1C, p. 23-25.
1982a: Relict ice scour marks and late phases of Lake Agassiz in northernmost Manitoba; Canadian Journal of Earth Sciences, v. 19, p. 1079-1087.
1982b: Trace element concentrations from overburden samples in northeastern Manitoba; in Current Research, Geological Survey of Canada, Paper 82-1A, p. 427-431.
1983a: Uranium and base metal concentrations in till samples from northern Manitoba; in Current Research, Geological Survey of Canada, Paper 83-1B, p. 303-307.
1983b: Uranium and base metal concentrations in till samples from Northern Manitoba; Geological Survey of Canada, Open File 931.
1983c: Character and development of northern Lake Agassiz and its relation to Keewatin and Hudson ice regimes; in Glacial Lake Agassiz, J. Teller and L. Clayton (ed.); Geolcgical Association of Canada, Special Paper 26, p. 117-131.
1988a: The buffering potential of carbonate soils in discontinuous permafrost terrain against natural and man-induced acidification; Proceedings, 5th International Permafrost Conference, Trondheim, v. 1, p. 564-567.
1988b: Drift carbonate on the Canadian shield II: carbonate dispersal and ice-flow patterns in northern Manitoba; Canadian Journal of Earth Sciences, v. 25, p. 783-787.

Dredge, L.A. and Cowan, W.R.
1989: Quaternary geology of the southwestern Canadian Shield; in Chapter 3 of Quaternary Geology of Canada and Greenland, R.J.Fulton (ed.); Geological Survey of Canada, Geology of Canada, no.1.

Dredge, L.A. and Grant, D.R.
1982: Glacial Lake Agassiz and Laurentide ice domains (abstract); in Programme with Abstracts, Geological Association of Canada, v. 7, p. 46.

Dredge, L.A and Nielsen, E.
1985: Glacial and interglacial deposits in the Hudson Bay lowlands: a summary of sites in Manitoba; in Current Research, Geological Survey of Canada, Paper 85-1A, p. 247-257.
1986: Gold concentrations in till, Great Island, northern Manitoba; in Current Research, Geological Survey of Canada, Paper 86-1A, p. 779-782.
1987a: The Churchill and Gillam areas, and glacial history, sea level record, periglacial geomorphology and archaeology of the Churchill area; 12th INQUA congress, Ottawa, field excursion C-13, p. 7-17.
1987b: Glacial and interglacial stratigraphy, Hudson Bay lowlands, Manitoba; D.L. Biggs (ed.); Geological Society of America, Centennial Field Guide-North Central Section, p. 43-46.

Dredge, L.A. and Nixon, F.M.
1979: Thermal sensitivity and the development of tundra ponds and thermokarst lakes in the Manitoba portion of the Hudson Bay lowlands; in Current Research, Geological Survey of Canada, Paper 79-1C, p. 23-26.
1980: Nature and distribution of sand and gravel, northeastern Manitoba; in Current Research, Geological Survey of Canada, Paper 80-1B, p. 283-286.
1981a: Surficial geology, Herchmer, Manitoba; Geological Survey of Canada, Map 1-1980.
1981b: Surficial geology, York Factory, Manitoba, Geological Survey of Canada, Map 2-1980.
1981c: Surficial geology, Cape Churchill, Manitoba; Geological Survey of Canada, Map 3-1980.
1981d: Surficial geology, Churchill, Manitoba; Geological survey of Canada, Map 4-1980.
1981e: Surficial geology, Caribou River, Manitoba; Geological Survey of Canada, Map 5-1980.
1982: Late glacial ice flow directions in northern Manitoba; Geological Association of Canada, Programme with Abstracts, Winnipeg, p.47.
Dredge, L.A., Morgan, A.V., and Nielsen, E.
1990: Sangamon and preSangamon interglaciations in the Hudson Bay lowlands of Manitoba; Géographie Physique et Quaternaire, v. 44.
Dredge, L.A., Nixon, F.M., and Richardson, R.J.
1986: Quaternary geology and geomorphology of northwestern Manitoba; Geological Survey of Canada, Memoir 418, 38 p.
Dyke, A.S., Dredge, L.A. and Vincent, J-S.
1982: Configuration of the Laurentide ice sheet during the Late Wisconsin maximum: Géographie Physique et Quaternaire, v. 36, p. 5-14.
Dyke, A.S. and Prest, V.K.
1987: Late Wisconsinan and Holocene history of the Laurentide Ice Sheet; Géographie Physique et Quaternaire, v. 41, p. 237-263.
Dyke, L.D.
1979: Bedrock heave in the central Canadian Arctic; in Current Research, Geological Survey of Canada, Paper 79-1A, p. 241-246.
1981: Bedrock heave in the central Canadian Arctic; in Current Research, Geological Survey of Canada, Paper 81-1A, p. 241-246.
1984: Frost heaving of bedrock in permafrost regions; Bulletin of the Association of Engineering Geologists, v. 21, p. 389-405.
1988: Permafrost aggradation along an emergent coast, Churchill, Manitoba; Proceedings, 5th International Permafrost Conference, Trondheim, v. 1, p. 138-142.
Hillaire-Marcel, C., and Fairbridge, R.W.
1978: Isostasy and eustasy of Hudson Bay; Geology, v. 6, p. 117-122.
Hansell, R.I., Scott, P.A., Svoboda, J. and Staniforth, R.
1983: Permafrost development in the intertidal zone at Churchill, Manitoba; Arctic, v. 36, p. p. 198-203.
Hobson, G.D.
1969: Seismic refraction results from the Hudson Bay region; Geological Survey of Canada, Paper 68-53, p. 227-246.
Hughes, O.L.
1965: Surficial geology of part of the Cochrane district of Ontario; Geological Society of America, Special Paper 84, p. 535-565.
Hussey, K.M. and Michelson, R.W.
1966: Tundra relief features near Point Barrow, Alaska; Arctic, v. 19, p. 162-184.
Johnston, G.H., and Brown, R.J.E.
1964: Some observations on permafrost distribution at a lake in the Mackenzie Delta, NWT; Arctic, v. 17, p. 162-175.
Kaszycki, C. and DiLabio, R.N.W.
1986: Surficial geology and till geochemistry, Lynn Lake-Leaf Rapids region, Manitoba; in Current Research, Part B, Geological Survey of Canada, Paper 86-1B, p. 245-256.
Klassen, R.W.
1983: Lake Agassiz and the late glacial history of northern Manitoba; in Glacial Lake Agassiz, J. Teller and L. Clayton (ed.); Geological Association of Canada, Special Paper 26.
1986: Surficial geology of north-central Manitoba; Geological Survey of Canada, Memoir 419, 57 p.
Klassen, R.A. and Shilts, W.W.
1977: Glacial dispersal of uranium in the District of Keewatin, Canada; in Prospecting in areas of glaciated terrain, Institute of Mining and Metallurgy, London, p. 80-88.
Lee, H.A.
1959: Surficial geology of southern District of Keewatin and the Keewatin ice divide; Geological Survey of Canada, Bulletin 51, 41 p.
1960: Late glacial and postglacial Hudson Bay sea episode; Science, v. 131, no. 3413, p. 1609-1611.
MacFarlane, I.C.
1969: Engineering characteristics of peat; Chapter 4 in Muskeg Engineering Handbook, University of Toronto Press, p. 78-126.
McDonald, B.C.
1969: Glacial and interglacial stratigraphy, Hudson Bay region; Geological Survey of Canada, Paper 68-53, p. 78-99.
1971: Late Quaternary stratigraphy and deglaciation in eastern Canada; in The Lake Cenozoic Glacial Ages, K.K.Turekian (ed.); Yale University Press, p. 331-353.
McInnes, W.
1913: The basins of Nelson and Churchill Rivers; Geological Survey of Canada, Memoir 30.
Manitoba Mineral Resources Division
1979: Geological map of Manitoba, scale 1:1000 000.
Nichols, H.
1967: The post-glacial history of vegetation and climate at Ennadai Lake, Keewatin, and Lynn Lake, Manitoba; Eiszeitalter und Gegenwart, Band 18, p. 176-197.
Nielsen, E.
1987: Till geochemistry of the Seal River area east of Great Island Manitoba; Manitoba Energy and Mines, Open File report OF-87-1, 28 p.
Nielsen, E. and Dredge, L.A.
1982: Quaternary stratigraphy and geomorphology of a part of the lower Nelson River; Geological Association of Canada, Field Trip Guide 5, Winnipeg, 56 p.
Nielsen, E. and Kroker, S.
1982: The drainage of Lake Agassiz and postglacial revegetation of a part of northeastern Manitoba; Geological Association of Canada, Programme with Abstracts, v. 7, p. 70.
Nielsen E. and Young, R.
1981: Quaternary geology and gravel resources inventory of the Thompson and Churchill areas; Manitoba Department of Energy and Mines, Report of field activities, p. 103-106.
Nielsen, E., Morgan, A.V., Morgan, A., Mott, R.J., Rutter, N.W., and Causse, C.
1986: Stratigraphy, paleoecology, and glacial history of the Gillam area, Manitoba; Canadian Journal of Earth Sciences, v. 23, p. 1641-1661.
O'Sullivan, O.
1907: On explorations along the proposed route of the Canadian National Railway between Split Lake and Fort Churchill, Manitoba; Geological Survey of Canada, Summary report for 1906, p. 87-98.
Peters, J. and McKeown, J.
1976: Glacial till and the development of the Nelson River; in Glacial till, R.F. Leggrtt (ed.); Royal Society of Canada, Special Publication no. 12, p. 364-380.
Paradis, S.
1980: Les depots meubles et la géomorphologie de la région de Churchill, Manitoba; thèse M.A. non Publiée, Université d'Ottawa.
Pelletier, B.R.
1969: Submarine physiography, bottom sediments and models of sediment transport; Geological Survey of Canada, Paper 68-53, p. 100-135.
Ringrose, S.
1975: A re-evaluation of late Lake Agassiz shoreline data from north central Manitoba; The Albertan Geographer, no. 11, p. 33-41.
Ritchie, J.C.
1962: A geobotanical survey of northern Manitoba; Arctic Institute of North America, Technical paper no. 9, 10 p.
Sanford, B.V., Norris, A.W., and Bostock, H.H.
1968: Geology of the Hudson Bay lowlands (Operation Winisk); Geological Survey of Canada, Paper 67-60, 118 p.

Sanger, F.J.
1963: Degree days and heat conduction in soils; Proceedings of the First International Conference on Permafrost, La Fayette, p. 253-262.
Schledewitz, D.C.P.
1977a: The Seal River area, Manitoba; Manitoba Department of Mines, Open File Report 77-3, 41 p.
1977b: Nejanilini-Caribou Lakes project; Manitoba Mineral Resources Division, Report of Field Activities, GS-1, p. 5-12.
1986: Geology of the Cochrane and Seal Rivers Area; Manitoba Department of Energy and Mines, Geology Report GR80-9, 139 p.
Seilman, P.V., Brown, J., Lewellan, R., McKim, H., and Merry, C.
1975: Classification and geomorphic implications of thaw lakes on the arctic coastal plain, Alaska; 45 Cold Regions Research and Engineering, Research Report 344, 21 p.
Shilts, W.W.
1981: Sensitivity of bedrock to acid precipitation: modification by glacial processes; Geological Survey of Canada, Paper 81-14, 7 p.
1984: Quaternary events Hudson Bay lowlands and southern Keewatin; in Quaternary stratigraphy of Canada, R.J. Fulton, (ed.); Geological Survey of Canada, Paper 84-10, p. 117-126.
Skinner, R.G.
1973: Quaternary stratigraphy of the Moose River Basin, Ontario; Geological Survey of Canada, Bulletin 225, 77 p.
Sugden, D.
1977: Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide ice sheet at its maximum; Arctic and Alpine Research, v. 9, p. 21-47.
Sugden, D. (cont'd.)
1978: Glacial erosion of the Laurentide ice sheet; Journal of Glaciology, v. 20, p. 367-391.
Taylor, F.C.
1961: Interglacial conglomerate in northern Manitoba, Canada; Geological Society of America, Bulletin, v. 72, p. 167-168.
Tyrrell, J.B.
1894: Notes on the Pleistocene of the north-west territories of Canada; Geological Magazine, v. 1, Decade 4, p. 394-399.
1898a: Report on the Doobaunt, Kazan, and Ferguson rivers and north-west coast of Hudson Bay; Geological Survey of Canada, Annual Report, v. 9, part F, p. 1-218.
1898b: The glaciation of north-central Canada; Journal of Geology, v. 6, p. 147-160.
1913a: Hudson Bay exploring expedition, 1912; Ontario Bureau of Mines, Report 22, 51 p.
1913b: The Patrician glacier south of Hudson Bay; Congrès géologique international, Compte rendu de la XII session, Canada, p. 523-534.
Wagner, F.J.E.
1967: Additional radiocarbon dates, Tyrrell Sea area; Maritime Sediments, v. 3, p. 100-104.
Williams, M.Y.
1948: The geological history of Churchill, Manitoba; Western Miner, v. 21, no. 6, p. 39-42.
Wright, J.F.
1932: Geology and mineral deposits of a part of southwestern Manitoba; Geological Survey of Canada, Memoir 169, p. 5-7.

APPENDIX

SECTION 1

Seal River, location 29/7/5 (58°54'N; 97°19'W). Surface elevation 230 m.

0 m	Sandy till	Very stony, grey sandy till containing sand laminae and sand inclusions. DU77-418. Carbonates = 3% matrix, 0% pebbles. Texture = 10% granules, 64% sand, 24% silt, 2% clay.
1.3 m	Glaciofluvial sediments	Plane and crossbedded sand, with gravel and silt layers. Beds dip NW and SE. DU77-419, 420. Texture = 2% granules, 93% sand, 5% silt and clay.
		-gradational contact-
5.3 m	Sandy till	Compact, olive grey, stony, silty sand till, with blocky to platy structure. Clasts subangular. DU77-423. Carbonates = 2% matrix, 0% pebbles. Texture = 5% granules, 64% sand, 26% silt, 5% clay.
9.5 m	Glacial-lacustrine sediments	Grey silt interbedded with beds of sorted sand.
10.0 m		covered
11.0 m	River level	

SECTION 2

North Knife River, location 5/8/1 (58°30.7'N; 96°45.5'W). Surface elevation 260 m.

0 m	Lake Agassiz sediments	Buff, medium to fine stratified sand. Planar beds dip to west.
1 m		Abraded subangular cobbles in sand matrix.
1.3 m		Massive, sorted sand and layers of desiccated clay.
		-sharp gradation-
2.5 m	Silt till	Olive-grey stony, stiff, gritty, fissile, silty till, becomes sandier with depth. DU77-462. Carbonate = 5% matrix, 25% granules. Texture = 4% granules, 31% sand, 60% silt-clay.
5.5 m	Sandy till	Poorly sorted sandy till, some fines. DU77-463. Carbonate = 10% matrix, 5% pebbles. Texture = 19% granules, 68% sand, 13% silt-clay.
7.5 m		covered
10.5 m	Interglacial gravels	Poorly sorted sand and gravel, cemented. Red oxidation at top, becoming grey with depth. Clasts round to subround. Grades down to loose, fine sand with plane beds. DU77-465.
12.0 m	End	

SECTION 3

North Knife River, section 6/8/2 (58°30.4'N, 96°41.5'W). Surface elevation 210 m.

0 m	Lake Agassiz sediments	Grey, silty sand with silt beds dipping south.
		-grades to-
1 m	Silt till	Very compact fissile olive stony till with a silty sand matrix. DU-77-470. Carbonate = 11% matrix, 7% pebbles. Texture = 2% granules, 45% sand, 33% silt, 20% clay.
5.5 m	Nelson River sediments	Dirty, very coarse bouldery gravel with a sandy matrix.
7.5 m	River level	

SECTION 4

North Knife River, location 7/8/1 (58°30.4'N; 96°40.6'W). Surface elevation 210 m.

0 m	Lake Agassiz sediments	Massive silt, grading to silt with granules. DU77-471. Carbonate = 9% matrix. Texture = 1% granules, 8% sand, 61% silt, 30% clay.
1.5 m	Sandy till	Compact, olive brown very stony silty-sand till. Clasts subangular to subround, many decomposed.
3.4 m		covered
5.0 m	Silt till	Intercalated sandy till and silty till, grading to silty till towards the base. DU77-472. Carbonate = 8% matrix, 4% pebbles. Texture = 8% granules, 68% sand, 20% silt, 4% clay.
8.1 m	Nelson River sediments	Rusty, oxidized strata of granules and pebbles.

SECTION 5

North Knife River, location 8/8/9 (58°30.5'N; 96°33.8'W). Saprolite. Surface elevation 180 m.

0 m	Lake Agassiz sediments	Compact, grey, fissile silt, grading to sandy silt. DU77-484. Carbonates = 23% matrix. Texture = 1% granules, 11% sand, 66% silt, 22% clay.
		-gradational contact-
1 m	Sky Pilot till	Blocky, compact stony silt till with red mudstone granules. Pebbles subangular to subround. DU77-485. Carbonate = 13% matrix. Texture = 3% granules, 23% sand, 40% silt, 34% clay.
3.8 m	Nelson River sediments	Rounded pebble gravel with sand. DU77-487. Texture = 18% granules, 71% sand, 11% silt and clay.
4.4 m	Saprolite	Yellow and blue toned saprolite and gruss. Kaolinized. Many large flakes of muscovite.
10 m	River level	

SECTION 6

North Knife River, location 9/8/4 (58°30.2'N; 96°21.0'W). Multiple tills and intertill sand units. Surface elevation 168 m.

0 m	Fluvial sediments	Crossbedded sand and redeposited saprolitic material.
1.0 m	Sandy till	Slightly stony, sandy till.
1.5 m		Wavy-bedded sorted sand.
2.4 m	Sandy till	Stony, sandy till.
2.9 m		Stratified sand.
3.4 m	Silty till	Grey silty till.
4.2 m	Sandy till	Sandy till.
5.5 m		Horizontally stratified sorted sand.

SECTION 7

North Knife River, location 10/8/1 (58°36.0'N; 96°17.0'W). Multiple tills. Surface elevation 152 m.

0 m	Lake Agassiz sediments	Grey silt, some dropstones.
		-gradational contact-
1.4 m	Sandy till	Loose, sandy till.
		-gradational contact-
3.5 m	Silty till	Fissile, grey, silty till with subangular boulders. Some zones are substratified. DU77-498. Carbonates = 11% matrix. Texture = 9% granules, 44% sand, 41% silt, 6% clay.
5.9 m	Nelson River sediments	Plastic silt.
6.3 m		Rusty, rounded pebble gravel with a sandy matrix.
11.5 m		Horizontally bedded silty clay and fine sand grading to massive sand.
14.5 m	River level	

SECTION 8

North Knife River, location 12/8/1 (58°33.9'N; 96°0.8'W). Surface elevation 130 m.

0 m	Tyrrell Sea sediments	Horizontally stratified sand and granules, slightly calcareous. Some ripple-drift structures near base, more crossbeds near top. Coarsening upwards sequence.
2.8 m		Poorly sorted sandy gravel.
3.3 m	Sandy till	Olive sandy till with sand blebs.
5.5 m		covered

6.0 m	Silty till	Stony silty till, subrounded clasts.
7.0 m		Grey silty sand.
8.0 m	Sandy till	Compact, blocky, grey, stony sandy till. DU77-508. Carbonates = 11% matrix, 4% pebbles. Texture = 13% granules, 77% sand, 10% silt and clay.
12.5 m	Silty till	Wet, gritty, grey silty till. DU77-509. Carbonates = 16% matrix. Texture = 3% granules, 38% sand, 35% silt, 24% clay.
14.0 m	River level	Start of oxidized gravels (Nelson River sediments).

SECTION 9

North Knife River, location 13/8/1 (58°33.5'N; 95°49.9'W). Surface elevation 110 m.

0 m	Tyrrell Sea sediments	Horizontally bedded, fossiliferous, grey silt and fine sand. DU77-513 (shells) and 512. Carbonates = 17% matrix. Texture = 25% sand, 57% silt, 17% clay.
1.5 m		Blocky, grey silty clay, fossiliferous. DU79-13, from base of unit. 7760 ± 140 BP (GSC-3070).
		-abrupt break-
4.0 m	Knife till	Grey, stony, clayey silt till. DU79-14. Carbonates = 24% matrix. Texture = 2% granules, 15% sand, 73% silt, 11% clay.
4.5 m		Large inclusions of varves in clayey till. Disturbed, contorted, and overturned red and grey varves.
7.5 m	Lake Agassiz sediments	Varve sequence, thickening and coarsening downwards. Alternating brick red and grey couplets, and some sand partings. Upper couplets about 2 cm thick. DU79-17 (grey). Carbonates = 21%. Texture = 7% sand, 86% silt, 7% clay. DU79-18 (red). Carbonates = 28%. Texture = 8% sand, 86% silt, 6% clay.
9.5 m		Middle zone has couplets 8-16 cm thick, becoming 20 cm thick at base. DU79-15 (red). Carbonates = 23%. Texture = 10% sand, 84% silt, 6% clay. DU79-16 (grey). Carbonates = 22%. Texture = 24% sand, 72% silt, 4% clay.
10.8 m		Fine sand with ripple drift structures indicating current to N.
12.5 m		Fine, rainbow-coloured sand in horizontal beds. Ice proximal unit.
		-sharp gradation -
14.5 m		Medium to coarse, fluvial sands, some cross beds. This unit emitted from subglacial conduit.
17.5 m	River level	

SECTION 10

South Knife River, location 19/7/5 (58°26.0'N; 95°52.0'W). Surface elevation 140 m.

0 m	Lake Agassiz sediments	Brown, stone-free silt.
		-sharp contact-
2 m		Loose, quasistratified sand and silty till.
		-gradational contact-
3.0 m	Silty till	Silty till with closely spaced, oxidized joint surfaces having black, irridescent stain. Moderately stony. DU78-265, 266. Carbonates = 10% matrix, 38% granules, 26% pebbles. Texture=3% granules, 38% sand,33% silt, 21% clay. WL=22; WP=13.
4.0 m		Silty till intercalated with sand beds.
4.5 m	Silty till	Vertical face of dark brown-black, very compact, silty till. Widely spaced joint surfaces with black, irridescent stain. Moderately stony. DU78-265, 266. Carbonates = 10% matrix, 38% granules, 26% pebbles. Texture = 3% granules, 43% sand, 33% silt, 21% clay. WL = 22; WP = 14; W = 7%
7.5 m	River level	

SECTION 11

Herriott Creek, location 6/7/8 (58°30.7'N; 95°03.8'W). Surface Elevation 85 m.

0 m	Tyrrell Sea sediments	Brown, medium sized, well sorted, uniform sand.
		-sharp contact-
0.8 m		Fossiliferous, grey silty clay of low plasticity. DU78-230, 233.
		-sharp contact-
1.8 m	Silty till	Compact, silty olive-brown till, crumbly structure. Few clasts. DU78-231, 232. Carbonates = 27% matrix, 54% granules, 65% pebbles. Texture = 3% granules, 35% sand, 43% silt, 19% clay. Qu = 3.0-4.0 kg/cm^2
4.4 m	Bedrock	Buff, flaggy, flat-lying limestone at river level.

SECTION 12

Munk River, location 18/7/12 (58°22.7'N; 94°24.1'W). Surface elevation 30 m.

0 m	Tyrrell Sea sediments	Grey, plastic, silty clay, with some shells.
		-gradational contact-
0.5 m	Silty till	Olive, sandy silt till, moderate compaction, low stone content. DU78-250, 253. Carbonates = 52% matrix, 82% granules, 88% pebbles. Texture = 3% granules, 30% sand, 50% silt, 17% clay. WL = 20; WP = 14.

2.0 m		Well sorted, brown sand.
2.1 m	Silty till	Grey-brown compact, stony till, joints spaced 5-10 cm apart, with surfaces oxidized rusty red. DU78-251, 252. Carbonates = 25% matrix, 42% granules, 81% pebbles. Texture = 3% granules, 35% sand, 46% silt, 21% clay. WL = 22; WP = 14; W = 9%.
4.5 m	River level	

SECTION 13

Long Island, Churchill River, location 4/7/7 (58°20.6′N; 94°18.4′W). Surface elevation 30 m.

0 m	Alluvium	Brown, horizontally stratified sand and silty sand.
1 m		Sand and rounded gravel, mostly granitic.
1.5 m		Well rounded, poorly sorted, cobble gravel. 30% carbonates.
2.5 m	Glaciomarine	Very sticky, plastic, gritty grey silt with some shells, becoming till-like near base, with more and larger clasts. DU78-112(upper part). Carbonate = 47%. Texture = 3% granules, 4% sand, 43% silt, 12% clay. DU-78-113 (lower part). Carbonate = 31% matrix, 80% pebbles. Texture = 3% granules, 31% sand, 48% silt, 18% clay.
		-sharp contact-
4.0 m	Silt till	Crumbly, slightly compact, stony silty till. Joints slightly oxidized. DU78-114. Carbonates = 34% matrix, 54% granules. Texture = 3% granules, 35% sand, 43% silt, 9% clay.
8.0 m	River level	

SECTION 14

Limestone Rapids, Churchill River, location 31/7/8 (58°12.2′N; 94°23.1′W). Surface elevation 30 m.

0 m	Estuarine	Silt and fine sand in plane beds. DU78-463, DU79-29.
2.0 m	Alluvium	Gravel
2.3 m	Silt till	Blocky, jointed very compact, grey-brown till. Not as stony as below. Joints unoxidized. DU79-28, DU78-464. Carbonates = 31% matrix, 58% pebbles. Texture = 2% granules, 32% sand, 43% silt, 23% clay. WL = 21; WP = 12. Till fabric N-S.
4.5 m	Silt till	Till becomes stonier. Oxidized joints. DU78-465, 466. Carbonates = 29% matrix, 45% pebbles. Texture = 3% granules, 34% sand, 42% silt, 21% clay. WL = 22; WP = 12. Till fabric E-W.
8.0 m	Nelson River sediments	Poorly sorted round to subangular gravel and sand.
8.7 m		Layers of detrital organics. DU79-30, DU78-467.
9.0 m		Round cobble and pebble gravel, massive.
		-undulatory truncation-

13.0 m	Amery till	Grey, blocky, very compact silt till with shell chips. Joints weathered. DU78-468, 469. DU79-27. Carbonates = 37% matrix, 52% granules, 89% pebbles. Texture = 10% granules, 29% sand, 47% silt, 22% clay. WL = 25; WP = 14.

SECTION 15

Churchill River borehole 80-1-3, Polar Gas. (58°0′N; 94°55′W). Surface elevation 90 m.

0 m	Tyrrell Sea sediments	Grey-brown stratified silty clay.
4.5 m	Lake Agassiz sediments	Brown silty sandy clay with gravel.
6.2 m	Sky Pilot till	Brown silty till.
11.0 m	Long Spruce till	Grey sandy silt till.
16.6 m	Glaciofluvial	Sand and gravel.
17.0 m	Long Spruce till	Grey silty sandy till, some gravel.
19.2 m	Nelson River sediments	Grey, uniform, silty sand.
21.1 m		Silty clay of low plasticity.
21.7 m		Sand, some gravel and silt.
25.0 m	End	

SECTION 16

Mountain Rapids, Churchill River (57°19.5′N; 95°48.2′W). Surface elevation 180 m.

0 m	Lake Agassiz sediments	Heavy, cohesive silt, laminated (DU79-37. DU84-22), interspersed with layers of silty diamicton (DU84-23)
		-erosional contact-
6 m	Silt till	Silty, brown, relatively uncompacted, unoxidized till. Few stones. Contains shell chips and Cretaceous clasts. DU79-36, DU78-363, 364, DU84-16, 19. Carbonates = 43% matrix, 70% pebbles. Texture = 2% granules, 6% sand, 70% silt, 22% clay, and 2% granules, 25% sand, 43% silt, 28% clay. WL = 27; WP = 16.
9.6 m	Intertill sand	Beds of yellowish sand and gravel, grey silt, and silty sand containing small peat balls and flattened carbonized sticks. DU79-35. 32 000 BP (GSC-3074). Organics have been transported.
10.0 m	Silt till	Compact, olive brown slightly oxidized, stony till with stained joints. Clasts include Cretaceous shale. DU79-34, DU84-14, 17. Carbonates = 41% and 53% matrix, 85% granules, 91% pebbles. Texture = 9% granules, 24% sand, 47% silt, 27% clay.
12.0 m	Intertill sand	Alternating beds of massive brown sand and injections of stony till. DU84-13.

15.0 m	Silt till	Grey till with oxidized joints, moderately stony. Contains shell chips of *Hiatella arctica*. DU79-33, DU84-12, 18. Carbonates = 36% and 49% matrix, 89% pebbles. Texture = 4% granules, 31% sand, 46% silt, 19% clay. Shells total isoleucene = 0.112-0.114.
18.0 m	Nelson River sediments	Disrupted gravel layers alternating with till at the top, grading down to plane beds of loose sand and gravel. Beds dip to east. Unit becomes sandier to base and contains reworked shell chips. DU79-32.
25 m	Silt till	Dark grey, compact, blocky, fissile silt till. Many granules, few stones. Widely spaced joints, oxidized deep red. DU79-31. Carbonates = 37% matrix, 81% pebbles. Texture = 4% granules, 24% sand, 43% silt, 29% clay.
28 m	River level	

SECTION 17

Little Beaver River. Location 24/7/1 (57°40.5'N; 95°35.5'W). Surface elevation 150 m.

0 m	Sky Pilot till	Olive brown stony till with many granules. Moderately compact, but crumbly. Thinly oxidized joint surfaces. Contains a sand bed. DU78-347, 348. Carbonates = 36% matrix, 93% pebbles. Texture = 2% granules, 26% sand, 40% silt, 32% clay. WL = 32, WP = 18. Qu = 3-4 kg/cm^2.
		-grades to-
4.0 m	Long Spruce till	Moderately compact, blocky grey till. Joints oxidized and spaced 5-8 cm apart. Low clast content. DU78-349, 350. Carbonates = 40% matrix, 54% granules, 92% pebbles. Texture = 3% granules, 33% sand, 45% silt, 19% clay. WL = 24; WP = 15. Qu = 4.5-5 kg/cm^2.
14.0 m	Silty till	Silty till with rusty brown joint surfaces. Clasts subangular. DU78-351. Carbonates = 33% matrix, 73% granules. Texture = 2% granules, 36% sand, 43% silt, 19% clay. WL = 23; WP = 16. Qu = 3.5-4 kg/cm^2.
18.0 m	River level	

SECTION 18

Little Churchill River, location 21/7/4 (57°22.0'N; 95°21.7'W). Surface elevation 145 m.

0 m	Lake Agassiz sediments	Brown silty clay with some granule-sized mudstone clasts.
		-gradational contact-
1 m	Sky Pilot till	Buff-brown, plastic clay till, very friable. Pebbles and granules present in low amounts. Joints are visible but are closed and unoxidized. DU78-299, 300. Carbonates = 31% matrix, 40% granules, 54% pebbles. Texture = 3% granules, 28% sand, 43% silt, 26% clay. WL = 26, WP = 14.
		-rapid gradation

4 m	Silt till	Jointed, very compact black till. Joint surfaces are irridescent with red-black haematite. Striated pebbles common. DU78-301, 302. Carbonate = 21% matrix, 52% granules, 69% pebbles. Texture = 3% granules, 34% sand, 40% silt, 23% clay. WL = 29. WP = 18.
		-sharp break-
7 m	Intertill sand	Crossbedded yellow sands, contorted by over riding ice. DU78-303.
7.3 m	Silt till	Very compact, jointed, black till, same as unit above. DU78-304. Carbonates = 83% pebbles.
10.0 m	?	Fine grey sand.
10.1 m	Silt till	Stony, black till, clasts mainly Paleozoic, many rounded.
12 m	River level	

SECTION 19

Little Churchill River, location 21/7/6 (57°16.0′N; 95°20.6′W). Surface elevation 170 m.

0 m	Sky Pilot till	Waterlaid glaciolacustrine till, grading downwards into brown silty till with few clasts. Stone content increases with depth. Crumbly structure. Vague oxidation lines but no visible joints. DU78-309, 310. Carbonates = 34% matrix, 55% granules, 62% pebbles. Texture=2% granules, 27% sand, 46% silt, 25% clay. WL = 26; WP = 15; W = 13%.
5 m	Silt till	Olive brown moderately compact, stiff fissile till. Incipient joints, weakly stained.
6.5 m	Intertill sand	Yellow-brown, medium grained, sorted sand. Planar strata.
		-sharp break-
6.8 m	Silt till	Very compact, dark grey till with many granules. Blocky structure with joints 8-10 cm apart. Rusty oxidation on joint surfaces.
7.0 m	Intertill sand	Thin wavy beds of yellow sand, intercalated with till
		-undulating erosional contact-
7.5 m	Silt till	Grey blocky silty till. DU78-312. Carbonates = 32% matrix, 50% granules. Texture = 3% granules, 39% sand, 43% silt, 15% clay. WL = 21; WP = 15; W = 9%.
		-abrupt contact-
9.0 m	Intertill sand	Brown sorted sands.
9.5 m	Silt till	Very compact, hard, grey stony till. DU78-313, 314. Carbonates=24% matrix, 56% granules, 79% pebbles. Texture = 3% granules, 45% sand, 39% silt, 14% clay. WL = 20; WP = 15; W = 10%.
18.8 m		covered
20 m	River level	

SECTION 20

Little Churchill River, location 28/7/8 (57°12.6'N; 95°19.6'W). Surface elevation 170 m.

0 m	Lake Agassiz sediments	Waterlaid till. Soft, brown, silty clay with a few granules. DU78-423, 424. Carbonates = 36% matrix, 51% pebbles. Texture = 2% granules, 26% sand, 49% silt, 23% clay. WL = 24; WP = 14.
		-grades to-
6 m	Sky Pilot till	Brown, plastic clay till, very few stones. Crumbly, slightly oxidized.
		-sharp break-
9 m	Intertill sand	Horizontally bedded and crossbedded medium-grained sorted sands, dipping down-river. Some beds consist of well-rounded pea gravel, about 35% carbonate. DU78-422.
14 m	Silt till	Dark grey compact silt till with more clasts than the till unit above. Breaks into small blocks. DU78-425, 426. Carbonates = 41% matrix, 51% granules, 92% pebbles. Texture = 3% granules, 37% sand, 45% silt, 15% clay.
		-sharp break-
17 m	Intertill sand	Sand
17.3 m	Silt till	Very hard, blocky black till with red oxidation stain along joint surfaces. DU78-427. Carbonates = 26% matrix. Texture = 2% granules, 24% sand, 42% silt, 32% clay.
20 m	River level	

SECTION 21

Deer River, location 4/7/4 (58°17.5'N; 94°11.4'W). Surface elevation 28 m.

0 m	Alluvium	Grey sandy silt, nonfossiliferous.
2 m		Rounded gravel and sand.
3 m	Glaciomarine	Fissile, grey silty diamicton, few stones. Uncompacted. Contains fragile marine pelecypod valves. DU78-107, 108. Carbonates = 39% matrix, 64% granules. Texture = 4% granules, 13% sand, 48% silt, 17% clay.
4 m	Silt till	Crumbly, gritty silty till, moderately compact. DU78-109. Carbonate = 25% matrix, 36% granules. Texture = 3% granules, 39% sand, 40% silt, 18% clay.
6 m	River level	

SECTION 22

Deer River, location 9/7/2 (57°36.5′N; 94°49.5′W). Surface elevation 180 m.

0 m	Lake Agassiz sediments	Soft, brown, crumbly, clayey waterlaid till. Few clasts. DU78-141, 142. Carbonates = 32% matrix. Texture = 3% granules, 32% sand, 43% silt, 22% clay. WL = 23; WP = 14. Qu = 1.5 kg/cm^2.
6 m	Sky Pilot till	Soft, brown silty till with sand laminae. DU78-143, 144. Carbonates = 28% matrix. Texture = 2% granules, 36% sand, 45% silt, 17% clay. WL = 21; WP = 15.
8 m		Bedded, sorted sand.
8.2 m	Silt till	Blocky, hard grey pebbly till with oxidized joints. DU78-139, 140. Carbonates = 30% matrix, 56% granules. Texture = 2% granules, 30% sand, 45% silt, 2% clay. WL = 23; WP = 15.
11 m	River level	

SECTION 23

Owl River at the Great Beach, location 31/7/5 (57°21.5′N; 94°15.4′W). Surface elevation 122 m.

0 m	Tyrrell Sea sediments	Active layer detachment slides in sandy, poorly sorted gravel. Clasts are subangular to subround, predominantly limestone.
2.4 m		Gritty grey nonfossiliferous clay.
2.8 m	Silt till	Blocky, grey, stony silty till with subangular to subround pebbles. DU78-458. Carbonates = 21% matrix, 26% granules. Texture = 3% granules, 43% sand, 38% silt, 6% clay. WL = 20; WP = 13; W = 11%.
		-gradational contact-
5.0 m	Silt till	Very blocky oxidized olive-grey till with subangular clasts. DU78-459. Carbonates = 39% matrix, 60% granules. Texture = 2% granules, 32% sand, 42% silt, 24% clay. WL = 25; WP = 14.
9 m	River level	

SECTION 24

Owl River at Silcox Creek, location 15/7/7 (57°41.6′N; 93°21.7′W). Surface elevation 45 m.

0 m		Dark brown moss peat.
0.5 m	Alluvium	Olive silt with fine sand.
0.8 m	Tyrrell Sea sediments	Uniform, brown sand with beds of sandy gravel. Fossiliferous. DU78-214, 215. 5310 ± 80 BP (GSC-3856).
1.8 m		Brown massive silt with some pebbles. DU78-216. Carbonates=33%. Texture = 2% granules, 32% sand, 53% silt, 13% clay. WL=19. WP = 15; W = 13%.
		-sharp contact-

2.5 m	Glaciomarine	Grey-brown blocky silt with sand lenses near top. Clasts subangular. Contains fragile shell fragments. DU78-217. Carbonates = 39% matrix. Texture = 2% granules, 32% sand, 44% silt, 21% clay. WL = 22; WP = 14; W = 10%.
3.5 m	Silt till	Very blocky, compact, oxidized, brown till. DU78-218. Carbonates = 35% matrix, 67% granules. Texture = 2% granules, 31% sand, 45% silt, 22% clay. WL = 22; WP = 15; W = 8%.
5 m	River level	

SECTION 25

Great Beach at Silcox, location 26/7/9 (57°08.3'N; 94°10.5'W). Surface elevation 125 m.

0 m	Tyrrell Sea sediments	Sorted sands interbedded with subangular to subround sandy gravels. Gravel 50% carbonate.
		-grades abruptly to-
1.5 m		Fossiliferous grey clay.
		-grades abruptly to -
2.1 m	Silt till	Olive, stony, silty till, moderately compact. DU78-394. Carbonates = 36% matrix. Texture = 4% granules, 35% sand, 49% silt, 12% clay.
2.8 m	End of pit	

SECTION 26

Harts Creek, Nelson River (57°01.0'N; 92°39.1'W). Surface elevation 10 m.

0 m	Tyrrell Sea sediments	Grey clayey silt, grading downwards to sand. DU78-435 (silt). Carbonate = 47%. Texture = 8% sand, 72% silt, 20% clay. DU78-436. Texture = 67% sand, 33% silt and clay.
1 m		Brown silt
1.5 m	Lag	Layer of striated cobbles, mostly Precambrian lithologies.
2.3 m	Sky Pilot till	Stony, brown crumbly, loosely compacted till. Unoxidized.
		-sharp gradation-
2.9 m		Sand lens.
3.0 m		Silty till, slightly oxidized.
4.0 m		Sand layer.
4.1 m	Silty till	Grey black till, moderated compaction, joints more heavily oxidized than in the till above. DU78-441, 442. Carbonates = 33% matrix, 32% granules, 59% pebbles. Texture = 2% granules, 32% sand, 55% silt, 11% clay.
9 m	Creek level	

SECTION 27

Port Nelson, Nelson River, site 2, 1984 (57°02.7′N; 92°36.6′W). Surface elevation 15 m.

0 m	Tyrrell Sea sediments	Laminated grey and brown silty sand, ice lenses. Fossiliferous estuarine deposits. 7020 ± 100 BP (GSC-3921).
1.5 m	Lake Agassiz sediments	Sandy diamicton. Well rounded pebbles in a poorly sorted sandy matrix.
		-sharp contact-
4.5 m	Sky Pilot till	Unoxidized,loose, stony brown till with stringers of fine sand. DU85-32, 33. Carbonates = 42% matrix, 75% granules. Texture = 2% granules, 31% sand, 45% silt, 22% clay.
6.5 m	Lag	Lag of imbricate cobbles, dipping east.
7.0 m	Sky Pilot till	Oxidized brown till, weakly jointed, less stony than till above. Breaks into small blocks. DU84-68. Carbonates = 35% matrix, 68% granules. Texture = 1% granules, 26% sand, 46% silt, 24% clay.
8.5 m	Intertill sand	Layer of massive yellowish sand and gravel. DU84-67.
9.1 m	Long Spruce till	Olive-brown till with subrounded stones, and clasts of grey silt. DU84-66. Carbonates = 38% matrix, 64% granules. Texture = 1% granules, 29% sand, 47% silt, 21% clay.
		-abrupt gradation-
9.7 m	Nelson River sediments	Faintly stratified grey, green and yellow silt containing pollen; overlying extremely poorly sorted gravel with rounded pebbles, and some shell chips. TL date about 40 000. DU84-65.
		-fuzzy contact-
11.1 m	Amery till	Olive till with thick red stain on joint surfaces. DU84-64, DU85-35. Carbonates = 39% matrix, 82% granules. Texture = 4% granules, 37% sand, 44% silt, 14% clay, and 2% granules, 27% sand, 46% silt, 25% clay.
14 m	Silt till	Exposed on tidal flats. DU85-38, 39. Carbonates = 36% and 45% matrix. Texture = 1% granules, 25% sand, 46% silt, 28% clay.

SECTION 28

Flamborough Head, Nelson River, site 3 (57°0.0′N; 92°40.3′W). Surface elevation 17 m.

0 m	Tyrrell Sea sediments	Fossiliferous grey marine silt. DU84-69, 79, 80. 7370 ± 90 BP (GSC-3930).
1 m	Lake Agassiz sediments	Gooey, soft, reddish silt and clay. DU84-78.
		-sharp contact-
2 m	Sky Pilot till	Unoxidized, crumbly, brown fissile till with sand seams. Very few stones. Unit contains shell chips. DU84-77, 79. Carbonates = 81% granules. Texture = 2% granules, 23% sand, 47% silt, 28% clay. Shells total isoleucene= 0.14,0.15,0.11,0.12.

4 m	Nelson River sediments	Bedded grey silt with yellow sand beds. Pollen bearing. Laterally equivalent unit nearby contains peat, detrital organics, and flattened sticks. DU84-165. TL date = 35 000.
4.6 m		Poorly sorted sand, grading downwards into layers of well sorted pea and pebble gravel. DU84-76.
		-sharp horizontal contact-
10.6 m		Brown diamicton (till?).
10.9 m		Steel-grey clay. DU84-75.
11.0 m	Silt till	Compact, fissile, grey-brown oxidized till with red staining along joints. Carbonates = 77% granules. Texture = 2% granules, 21% sand, 41% silt, 34% clay.
15 m		covered
17 m	River level	Precambrian boulders along riverbank.

MAPS
NOT
FILMED

CARTES
OMISES